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REFRACTION AND REFLECTION OF SEISMIC WAVES* I. FUNDAMENTALS

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ABSTRACT

We give in this paper an exposition of the fundamental theory underlying the theory of reflection and refraction seismic waves. It was thought useful to include material not strictly new along with the new material, because the sources are not easily obtained by many readers of this magazine. Knott's energy equation is given a simple interpretation. Conditions at the interface are discussed together with the limitations of these conditions, as conditions by which our problem is to be solved. It appears that the energy flow must be considered as well as the interface conditions.

INTRODUCTION

This is a subject which most geophysicists must feel is in a very incomplete state. There was a time in the history of the development of optical theory, when it was felt necessary to make careful experiments in optical refraction and reflection. Although the theory of elastic wave reflection is about fifty years old,[1] precise controlled experimental work seems not yet to have been born. Neither earthquake studies nor prospecting studies have shed definite light on the subject. There is great need for precise experiments on scale models where conditions are carefully controlled.

The geophysical prospector generally is only interested in getting records of "sufficiently strong" reflections or refractions to select the beginning of the pulse accurately. If he is required to distinguish between a deep simple reflection and a medium double reflection, his best aid is apt to be some knowledge of intensities to be expected for

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[1] C. G. Knott, *Philosophical Magazine*, 1899.

the two cases. Why does an interface give an extremely weak reflection but give a large refraction pulse? Does the refracted path follow the interface strictly, or does it follow the path of least time? This is a matter of great practical importance, since the answer may decide between a large and a small fault throw.

This paper is in part an exposition of the fundamental theory, and in part, new points of view and new applications. Previous applications of the theory have placed emphasis on earthquake interpretations. Here, emphasis is placed on prospecting problems. It is hoped that someone with the facilities for experimental research will see the need for such, and devise test experiments.

GENERAL ASPECTS OF THE THEORY

The foundation is, of course, the theory of elasticity. This great theory is developed along directions not altogether suitable for geophysical applications. The concept of isotropy plays too prominent a part. An elastic medium is *isotropic at a point* P, if its density, resistance to compression, and resistance to shear at M near P on any ray issuing from P, are each independent of the direction of the ray. At an interface between two isotropic elastic solids, the medium is certainly not isotropic. Here we see that the definition given is not a good one, because all the physical quantities used in the definition are themselves not defined there at the interface. We must then add the condition that the three quantities must be definable before the medium can be isotropic.

Within an isotropic medium, the symmetry of the stress and strain is easily established. A consequence of this symmetry is the well known result that, by a proper choice of axes of coordinates at a point, all shear quantities can be eliminated. These principal axes are the same for the stress as for the strain. The principal stresses are tensions or compressions. The conceptual simplification thus introduced is very large.

What is the behavior of stresses and strains at an interface? The stress normal to the interface is continuous. If this were not true, we should have an infinite acceleration at the interface. Normal stress to an element of area perpendicular to the interface is not necessarily continuous. Consider two long rods of equal square cross-section and equal Poisson ratios. Place the rods in contact side by side, and apply tensions to the two rods, so that the displacements are continuous across the contact. Evidently, whenever the two Young's Moduli

are different, the tensions will be different, and so the stress is discontinuous. When we postulate no slipping at the interface, the displacement is continuous there, and all derivatives of displacements taken in a direction parallel to the interface are continuous (this is not a general proposition, but it covers the cases of physical interest). We can establish the continuity of the tangential stress to a surface parallel to the interface, by showing that any discontinuity implies an infinite tangential acceleration at the interface.

The above considerations are sufficient to enable us to calculate how the orientation of principal axes changes, on crossing an interface. For this, we shall need some preliminary ideas.

Rotation of coordinate axes is a familiar idea. When such a rotation is carried out, the stress and strain components undergo a transformation, since they are defined in terms of the coordinates. Since we shall consider in this paper only two-dimensional strains, and since the stress and strain have the same principal axes in isotropic media, it will be sufficient to consider one principal axis of stress to be already known, and for that axis the strain is zero. This, then, is our axis of rotation. Let the strain be written in the form

$$\begin{pmatrix} \epsilon_x, & \frac{1}{2}\epsilon_{xy} \\ \frac{1}{2}\epsilon_{yx}, & \epsilon_y \end{pmatrix} = \begin{pmatrix} \frac{\partial u}{\partial x}, & \frac{1}{2}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right), & \frac{\partial v}{\partial y} \end{pmatrix}. \quad (1)$$

We are using here the notation of matrices, because it has the advantage of simplicity. A very readable account of matrices is found in Bocher's "Introduction to Higher Algebra." Let

$$\begin{pmatrix} a_{11}, & a_{12} \\ a_{21}, & a_{22} \end{pmatrix} = (a_{ij})$$

so that the first subscript denotes the row and the second the column. Two matrices are then equal when corresponding elements are equal. The sum of two matrices is

$$(a_{ij}) + (b_{ij}) = (a_{ij} + b_{ij}). \quad (2)$$

Products are formed as follows:

$$(a_{ik})(b_{kj}) = \left(\sum_{k=1}^{2} (a_{ik}b_{kj}) \right) \quad (3)$$

also,

$$(x_1,\ x_2)\begin{pmatrix} a_{11},\ a_{12} \\ a_{21},\ a_{22} \end{pmatrix} = (x_1a_{11} + x_2a_{21},\ x_1a_{12} + x_2a_{22})$$
$$\begin{pmatrix} a_{11},\ a_{12} \\ a_{21},\ a_{22} \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} a_{11}x_1 + a_{12}x_2 \\ a_{21}x_1 + a_{22}x_2 \end{pmatrix}. \tag{3'}$$

considering the last expression, we see that the rotation equations

$$\begin{aligned} x' &= x\cos\theta + y\sin\theta \\ y' &= -x\sin\theta + y\cos\theta, \end{aligned} \tag{4}$$

can be written in the matrix form

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\theta,\ \sin\theta \\ -\sin\theta,\ \cos\theta \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix}. \tag{5}$$

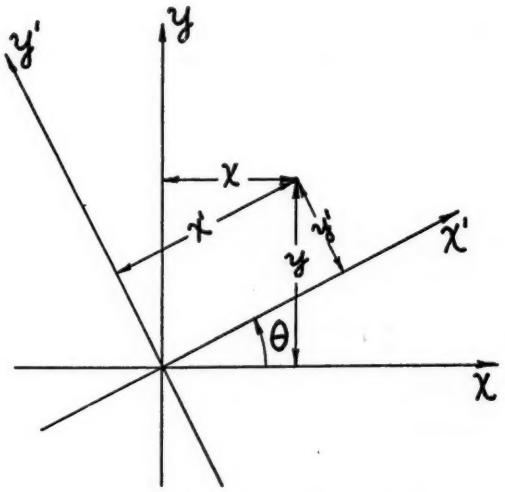

FIG. 1. Rotation of coordinate axes.

The reverse rotation is obtained by changing the sign of θ, and is then

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos\theta, & -\sin\theta \\ \sin\theta, & \cos\theta \end{pmatrix}\begin{pmatrix} x' \\ y' \end{pmatrix}. \tag{6}$$

Note that

$$\begin{pmatrix} \cos\theta,\ \sin\theta \\ -\sin\theta,\ \cos\theta \end{pmatrix}\begin{pmatrix} \cos\theta, & -\sin\theta \\ \sin\theta, & \cos\theta \end{pmatrix} = \begin{pmatrix} 1, & 0 \\ 0, & 1 \end{pmatrix}. \tag{7}$$

Now any matrix represents some kind of transformation; thus

$$\begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \tag{8}$$

is a linear mapping of one region on another (in this case, we imagine the coordinate system fixed but the points of the region moved). If now we rotate coordinates through an angle θ, we may also express (8) in the new system. Let us observe that the rotation corresponds to the following alterations:

$$\begin{pmatrix} x \\ y \end{pmatrix} \to \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\theta, & \sin\theta \\ -\sin\theta, & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix},$$

$$\begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} \to \begin{pmatrix} \bar{x}' \\ \bar{y}' \end{pmatrix} = \begin{pmatrix} \cos\theta, & \sin\theta \\ -\sin\theta, & \cos\theta \end{pmatrix} \begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix}$$

and $\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \to \begin{pmatrix} a_{11}' & a_{12}' \\ a_{21}' & a_{22}' \end{pmatrix}$ where $\begin{pmatrix} a_{11}' & a_{12}' \\ a_{21}' & a_{22}' \end{pmatrix}$ is selected

so that

$$\begin{pmatrix} \bar{x}' \\ \bar{y}' \end{pmatrix} = \begin{pmatrix} a_{11}' & a_{12}' \\ a_{21}' & a_{22}' \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix} \tag{8'}$$

is equivalent to (8) (that is, performs the same mapping as (8)). Note that (8′) is

$$\begin{pmatrix} \cos\theta, & \sin\theta \\ -\sin\theta, & \cos\theta \end{pmatrix} \begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} = \begin{pmatrix} a_{11}' & a_{12}' \\ a_{21}' & a_{22}' \end{pmatrix} \begin{pmatrix} \cos\theta, & \sin\theta \\ -\sin\theta, & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

or, multiplying on the left by the reverse rotation matrix, and making use of (7), we get

$$\begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} = \begin{pmatrix} \cos\theta, & -\sin\theta \\ \sin\theta, & \cos\theta \end{pmatrix} \begin{pmatrix} a_{11}' & a_{12}' \\ a_{21}' & a_{22}' \end{pmatrix} \begin{pmatrix} \cos\theta, & \sin\theta \\ -\sin\theta, & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}. \tag{9}$$

Thus,

$$\begin{pmatrix} a_{11}, & a_{12} \\ a_{21}, & a_{22} \end{pmatrix} = \begin{pmatrix} \cos\theta, & -\sin\theta \\ \sin\theta, & \cos\theta \end{pmatrix} \begin{pmatrix} a_{11}', & a_{12}' \\ a_{21}', & a_{22}' \end{pmatrix} \begin{pmatrix} \cos\theta, & \sin\theta \\ -\sin\theta, & \cos\theta \end{pmatrix} \tag{10}$$

or,

$$\begin{pmatrix} a_{11}', & a_{12}' \\ a_{21}', & a_{22}' \end{pmatrix} = \begin{pmatrix} \cos\theta, & \sin\theta \\ -\sin\theta, & \cos\theta \end{pmatrix} \begin{pmatrix} a_{11}, & a_{12} \\ a_{21}, & a_{22} \end{pmatrix} \begin{pmatrix} \cos\theta, & -\sin\theta \\ \sin\theta, & \cos\theta \end{pmatrix}. \quad (10')$$

Thus matrices transform according to (10'), and vectors according to (5), by a rotation of coordinates through an angle θ.

We now suppose that $a_{12} = a_{21}$ (i.e., that the matrix is symmetrical), and find θ such that $a_{12}' = a_{21}' = 0$. That is, we find the direction of the principal axes. Note that the right hand side of (10') multiplied out and reduced gives

$$\begin{pmatrix} a_{11}', & a_{12}' \\ a_{21}', & a_{22}' \end{pmatrix} = \begin{pmatrix} \cos^2\theta a_{11} + \sin 2\theta a_{12} + \sin^2\theta a_{22}, & \cos 2\theta a_{12} - \tfrac{1}{2}\sin 2\theta(a_{11} - a_{22}) \\ \cos 2\theta a_{12} - \tfrac{1}{2}\sin 2\theta(a_{11} - a_{22}), & \sin^2\theta a_{11} - \sin 2\theta a_{12} + \cos^2\theta a_{22} \end{pmatrix}. \quad (11)$$

Thus $a_{12}' = 0$ when

$$\tan 2\theta = 2a_{12}/(a_{11} - a_{22}) \quad (12)$$

which determines θ. Knowing θ, the principal values a_{11}', a_{22}' can be easily calculated by (11).

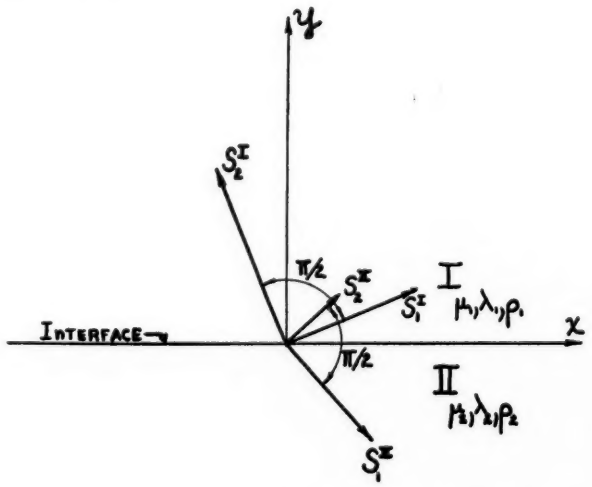

FIG. 2. Illustrating sudden change in principal stresses and their orientation at an interface.

We are now prepared to consider a little more in detail what happens at an interface. Consider Media I and II with elastic constants and densities $(\mu_1, \lambda_1, \rho_1)$ and $(\mu_2, \lambda_2, \rho_2)$ respectively. Take, for the moment, coordinates, so that the (x, z)-plane is the interface. Then, applying Hooke's Law in both media, we get

$$\begin{pmatrix} S_x^{\mathrm{I}}, & S_{xy}^{\mathrm{I}}, & 0 \\ S_{xy}^{\mathrm{I}}, & S_y^{\mathrm{I}}, & 0 \\ 0, & 0, & S_z^{\mathrm{I}} \end{pmatrix}$$

$$= 2\mu_1 \begin{pmatrix} \dfrac{\partial u^{\mathrm{I}}}{\partial x}, & \dfrac{1}{2}\left(\dfrac{\partial u^{\mathrm{I}}}{\partial y}+\dfrac{\partial v^{\mathrm{I}}}{\partial x}\right), & 0 \\ \dfrac{1}{2}\left(\dfrac{\partial u^{\mathrm{I}}}{\partial y}+\dfrac{\partial v^{\mathrm{I}}}{\partial x}\right), & \dfrac{\partial v^{\mathrm{I}}}{\partial y}, & 0 \\ 0, & 0, & 0 \end{pmatrix} + \lambda_1 \Delta^{\mathrm{I}} \begin{pmatrix} 1, 0, 0 \\ 0, 1, 0 \\ 0, 0, 1 \end{pmatrix} \tag{13}$$

$$\begin{pmatrix} S_x^{\mathrm{II}}, & S_{xy}^{\mathrm{II}}, & 0 \\ S_{xy}^{\mathrm{II}}, & S_y^{\mathrm{II}}, & 0 \\ 0, & 0, & S_z^{\mathrm{II}} \end{pmatrix}$$

$$= 2\mu_2 \begin{pmatrix} \dfrac{\partial u^{\mathrm{II}}}{\partial x}, & \dfrac{1}{2}\left(\dfrac{\partial u^{\mathrm{II}}}{\partial y}+\dfrac{\partial v^{\mathrm{II}}}{\partial x}\right), & 0 \\ \dfrac{1}{2}\left(\dfrac{\partial u^{\mathrm{II}}}{\partial y}+\dfrac{\partial v^{\mathrm{II}}}{\partial x}\right), & \dfrac{\partial v^{\mathrm{II}}}{\partial y}, & 0 \\ 0, & 0, & 0 \end{pmatrix} + \lambda_2 \Delta^{\mathrm{II}} \begin{pmatrix} 1, 0, 0 \\ 0, 1, 0 \\ 0, 0, 1 \end{pmatrix} \tag{14}$$

where $\Delta^{\mathrm{I}} = \partial u^{\mathrm{I}}/\partial x + \partial v^{\mathrm{I}}/\partial y$ and $\Delta^{\mathrm{II}} = \partial u^{\mathrm{II}}/\partial x + \partial v^{\mathrm{II}}/\partial y$. Now we have seen that $S_y^{\mathrm{I}} = S_y^{\mathrm{II}}$ and $S_{xy}^{\mathrm{I}} = S_{xy}^{\mathrm{II}}$ at the interface. Also,

$$\partial u^{\mathrm{I}}/\partial x = \partial u^{\mathrm{II}}/\partial x \text{ and } \partial v^{\mathrm{I}}/\partial x = \partial v^{\mathrm{II}}/\partial x.$$

Hence we have

$$2\mu_1(\partial v^{\mathrm{I}}/\partial y)+\lambda_1\Delta^{\mathrm{I}} = S_y^{\mathrm{I}} = S_y^{\mathrm{II}} = 2\mu_2(\partial v^{\mathrm{II}}/\partial y)+\lambda_2\Delta^{\mathrm{II}} \text{ at } y=0 \tag{15}$$

or

$$(2\mu_1 + \lambda_1)(\partial v^{\mathrm{I}}/\partial y) + \lambda_1(\partial u^{\mathrm{I}}/\partial x) = (2\mu_2 + \lambda_2)(\partial v^{\mathrm{II}}/\partial y) + \lambda_2(\partial u^{\mathrm{I}}/\partial x),$$

or

$$\partial v^{\mathrm{II}}/\partial y = \{(\lambda_1-\lambda_2)(\partial u^{\mathrm{I}}/\partial x)+(2\mu_1+\lambda_1)(\partial v^{\mathrm{I}}/\partial y)\}/(2\mu_2+\lambda_2) \text{ at } y=0 \tag{16}$$

Also,

$$\Delta^{II} = \partial u^I/\partial x + \partial v^{II}/\partial y$$

or,

$$\Delta^{II} = \{(2\mu_2+\lambda_1)(\partial u^I/\partial x)+(2\mu_1+\lambda_1)(\partial v^I/\partial y)\}/(2\mu_2+\lambda_2) \text{ at } y=0. \quad (17)$$

Furthermore, we have

$$\mu_1((\partial u^I/\partial y) + (\partial v^I/\partial x)) = \mu_2((\partial u^{II}/\partial y) + (\partial v^{II}/\partial x)) \text{ at } y = 0 \quad (18)$$

so

$$\partial u^{II}/\partial y = (\mu_1/\mu_2)(\partial \mu^I/\partial y) + ((\mu_1 - \mu_2)/\mu_2)(\partial v^I/\partial x) \text{ at } y = 0. \quad (19)$$

Thus we have determined all the strain terms on one side in terms of strain terms on the other. Hence we know also the stress on the two sides of the interface when we know it on one side.

Now, suppose we have to rotate the x-axis through θ^I degrees, to reach the first principal axis of strain in medium I. Then there will be determined an angle θ^{II}, through which the x-axis must be rotated to reach the first principal axis of strain in medium II. We may write the two matrices in the forms

$$\begin{vmatrix} \dfrac{\partial u^I}{\partial x}, & \dfrac{1}{2}\left(\dfrac{\partial u^I}{\partial y}+\dfrac{\partial v^I}{\partial x}\right) \\ \dfrac{1}{2}\left(\dfrac{\partial u^I}{\partial y}+\dfrac{\partial v^I}{\partial x}\right), & \dfrac{\partial v^I}{\partial y} \end{vmatrix}; \quad (20)$$

$$\begin{vmatrix} \dfrac{\partial u^I}{\partial x}, & \dfrac{\mu_1}{\mu_2}\dfrac{1}{2}\left(\dfrac{\partial u^I}{\partial y}+\dfrac{\partial v^I}{\partial x}\right) \\ \dfrac{\mu_1}{\mu_2}\dfrac{1}{2}\left(\dfrac{\partial u^I}{\partial y}+\dfrac{\partial v^I}{\partial x}\right), & \dfrac{1}{2\mu_2+\lambda_2}\left\{(\lambda_1-\lambda_2)\dfrac{\partial u^I}{\partial x}+(2\mu_1+\lambda_1)\dfrac{\partial v^I}{\partial y}\right\} \end{vmatrix}. \quad (21)$$

Applying (12), we obtain

$$\tan 2\theta^I = \{(\partial u^I/\partial y) + (\partial v^I/\partial x)\}/\{(\partial u^I/\partial x) - (\partial v^I/\partial y)\} \quad (22)$$

$$\tan 2\theta^{II} = (\mu_1/\mu_2)\{(\partial u^I/\partial y) + (\partial v^I/\partial x)\}/[(\partial u^I/\partial x) - \{(\lambda_1 - \lambda_2)(\partial u^I/\partial x) + (2\mu_1 + \lambda_1)(\partial v^I/\partial y)\}/(2\mu_2 + \lambda_2)]. \quad (23)$$

Equations (22) and (23) are of considerable interest in connection with the theory of the internal structure of the earth. Mention may also be made of unexplained effects due to high pressure in P. W.

Bridgeman's "The Physics of High Pressure" (see for instance pages 88–90). As long as we restrict ourselves to low pressure and low shear, we run into no difficulties by regarding many substances as isotropic. However, we know that the ideal homogeneous isotropic elastic solid is an ideal concept, and that as we consider smaller and smaller dimensions, all actual substances diverge more and more from this ideal. If we introduced a tiny cube of different elastic constants into an

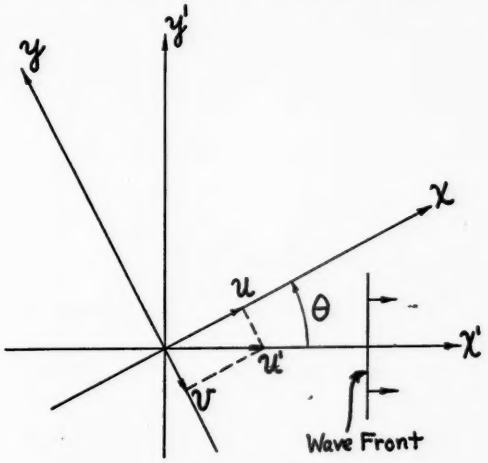

FIG. 3. Longitudinal wave travelling in the x'-direction, showing resultant displacement u' and its components, u and v.

isotropic cylinder with a cavity, so that the small cube was near the cavity wall, and applied hydrostatic pressure to the outside, the shear introduced by the discontinuity would cause the flaking off of this small cube, and details of the process can be worked out to a first approximation by applying (22) and (23). However, we reserve this discussion for another paper, and pass directly to problems nearer to geophysical prospecting.

Consider a plane compressional wave propagated in the x'-direction. We can show in this case that the only non-zero displacement component is that in the x'-direction, and this we may take in the form

$$u'(x', t) = u_0'(\exp)(2\pi i(t - (x'/v))/T). \qquad (24)$$

If we rotate axes through an angle θ

$$x' = \cos\theta x - \sin\theta y,$$

so (24) becomes

$$u'(x, y, t) = u_0'(\exp)(2\pi i(t - (x \cos\theta - y \sin\theta)/v)/T). \qquad (25)$$

The displacement, being a vector, we find its components in any direction by forming the projection on this direction. Thus

$$u' \cos\theta, \qquad -u' \sin\theta \qquad (26)$$

are the components of displacement in the x- and y-directions respectively. Thus

$$\left.\begin{aligned} &u = u' \cos\theta,\ v = -u' \sin\theta,\ \partial u/\partial x = -2\pi i \cos^2\theta u'/Tv \\ &\partial v/\partial y = -2\pi i \sin^2\theta u'/Tv, \\ &\partial u/\partial y = \pi i \sin 2\theta u'/Tv,\ \partial v/\partial x = \pi i \sin 2\theta u'/Tv \end{aligned}\right\} \qquad (27)$$

so that for this case, (22) is

$$\tan 2\theta^{I} = -\tan 2\theta.$$

The change of sign results when primed and unprimed coordinates are exchanged. (23) becomes

$$\tan 2\theta^{II} = (\mu_1/\mu_2) \sin 2\theta / \{(((2\mu_1 + \lambda_1)/(2\mu_2 + \lambda_2)) \sin^2\theta - (1 - (\lambda_1 - \lambda_2)/(2\mu_2 + \lambda_2)) \cos^2\theta\}. \qquad (28)$$

In case $\mu = \lambda$, (28) becomes (when put into a form suitable for numerical computation),

$$\cot 2\theta^{II} = (4(\mu_2/\mu_1) - 1)(1/6) \cos\theta^{I} - (1/2) \tan\theta^{I}. \qquad (29)$$

Fig. 4 gives θ^{II} for values of θ^{I} and (μ_2/μ_1).

We shall next consider a transverse wave polarized in the plane of incidence, i.e., such that the displacement has only x and y components and not a z component. Such a wave has its displacement in a vertical plane through the surface trace in seismic work, and is termed an SV wave by Jeffreys.[2] The shear wave, polarized in the horizontal plane, is the SH wave.

It can easily be shown that all the displacement in an SV wave is perpendicular to the ray or direction of propagation. If x' is the direction of propagation, the displacement is

$$v'(x', t) = v_0'(\exp)(2\pi i(t - x'/v_1)/T). \qquad (30)$$

[2] H. Jeffreys, "The Earth," 2nd ed., p. 86.

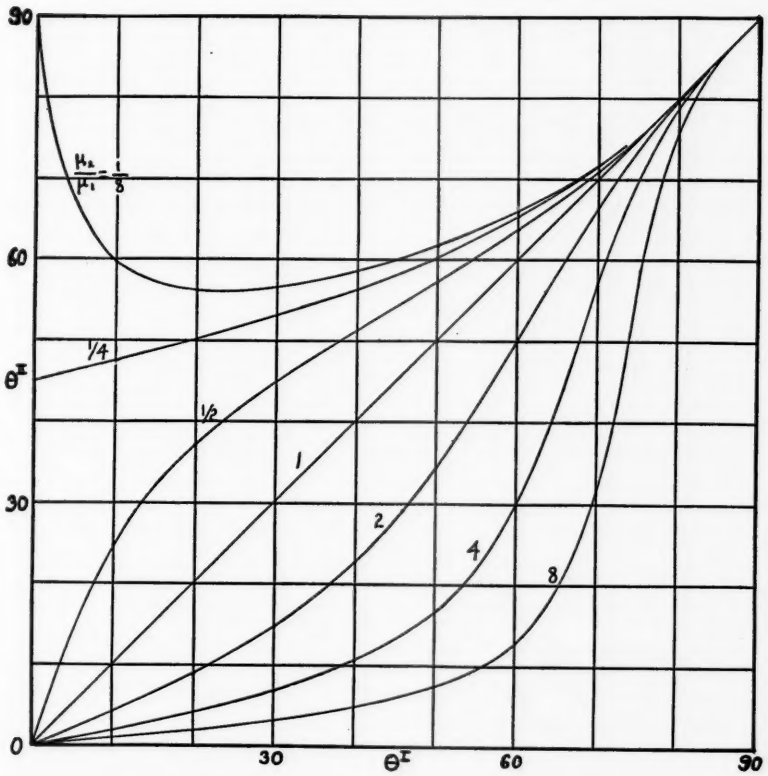

FIG. 4. This shows how the principal axes are turned at an interface when the incident wave is longitudinal and the reflected parts are neglected. Graph of (29).

As before, if we rotate axes, we get

$$v'(x, y, t) = v_0(\exp)(2\pi i(t - (x \cos\theta - y \sin\theta)/v_1)/T), \quad (31)$$

and the displacement components are

$$u = v' \sin\theta, \qquad v = v' \cos\theta. \quad (32)$$

Hence,

$$\begin{aligned} \partial u/\partial x &= -\pi i \sin 2\theta v'/Tv_1, & \partial v/\partial y &= -\partial u/\partial x, \\ \partial u/\partial y &= 2\pi i \sin^2\theta v'/Tv_1, & \partial v/\partial x &= -2\pi i \cos^2\theta v'/Tv_1 \end{aligned} \quad (33)$$

so (23) becomes

$$\tan 2\theta^{II} = (\mu_1/\mu_2)(2\mu_2 + \lambda_2)/(\mu_2 + \lambda_2 + \mu_1)) \cot 2\theta. \quad (34)$$

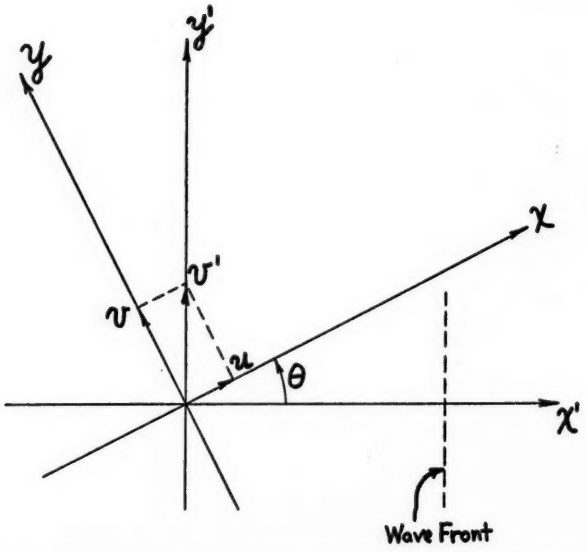

FIG. 5. Transverse wave travelling in the x'-direction, showing resultant displacement v' and its components, u and v.

The cotangent appears here, because we are getting the principal axes, which make an angle of 45° with the direction of maximum shear. This fact is most important to keep in mind, in picturing the process. Thus in an SV-wave, the principal axes in the plane of incidence make angles of 45° with the ray.

Fig. 6 gives θ^{II} in terms of θ for the case where $\mu_1=\lambda_1$ and $\mu_2=\lambda_2$. It will be noted that the rotation is quite different in the two cases. Or more generally, θ^{II} is partly determined by the relationship between the derivatives of u^I and v^I. The exceptional case is, of course, that where $\mu_1=\mu_2$, $\lambda_1=\lambda_2$ with $\rho_1\neq\rho_2$. Here, $\theta^I=\theta^{II}$, as is evident. However, this case has been worked out by C. G. Knott,[3] when $\rho_2=(\frac{1}{2})\rho_1$, with the result that an incident wave of either shear or compression type is split into the usual four waves.

We should observe at this point that the density has no effect on the rotation of the principal axes at an interface. Hence in general, Snell's Law is not connected with the amount of rotation.

Let us consider an *energy* associated with a train of waves. Plane and spherical waves have an important property, namely, if we form a tube of rays closed by wave fronts, then the total energy in this

[3] C. G. Knott, *loc. cit.*

tube remains constant as the tube moves with the wave. Hence if we picture the process according to Huygen's Principle, we must suppose that the energy flowing into the tube is equal to that flowing out of the tube. We may now deduce a pair of energy equations due to Knott, and thus interpret them in a most simple manner.

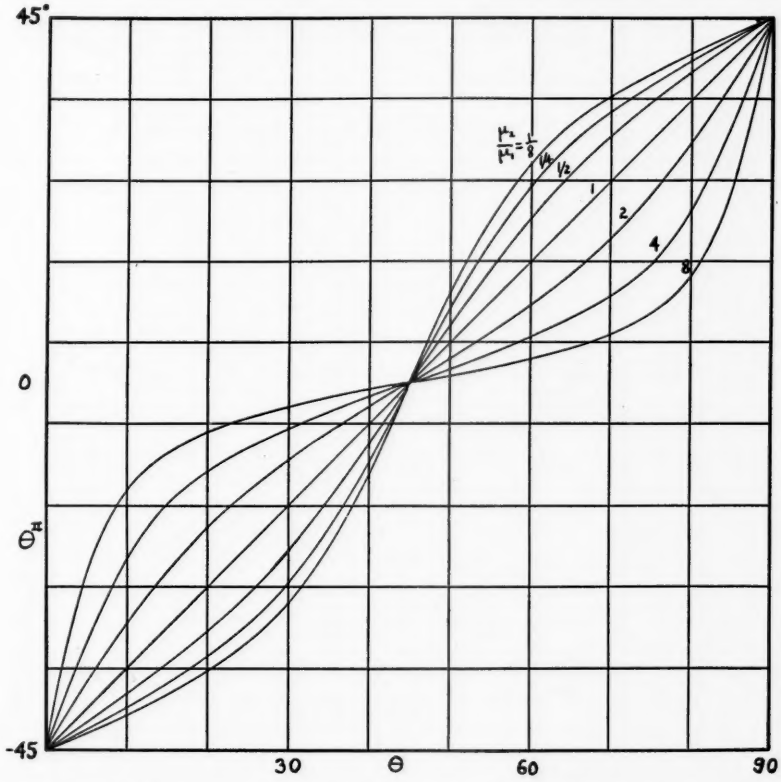

FIG. 6. This shows how the principal axes are turned at an interface when the incident wave is longitudinal and reflected parts are neglected. Graph of (34) with $\mu_1=\lambda_1$ and $\mu_2=\lambda_2$.

Refer to Fig. 7. Here, the rectangle IL represents a tube of incident compressional waves ($\frac{1}{2}$) wave-length long, and of such a width that its capping wave-fronts strike an interval of unit length at the intersection of the plane of incidence with the surface. Then, after two complete periods, we suppose that this energy is to be found partitioned in the rectangles RL, RT, DL, and DT corresponding to re-

flected longitudinal, reflected transverse, refracted longitudinal, and refracted transverse, waves, with velocities a_1, b_1, a_2, and b_2 respectively. The energies are easily calculated. If

$$u = A \cos (2\pi(t - x/v)/T + \theta),$$

the energy E is

$$E = \rho \int_{x_1}^{x_1+Tv/2} u^2 dx = \pi^2 \rho v A^2/T. \tag{35}$$

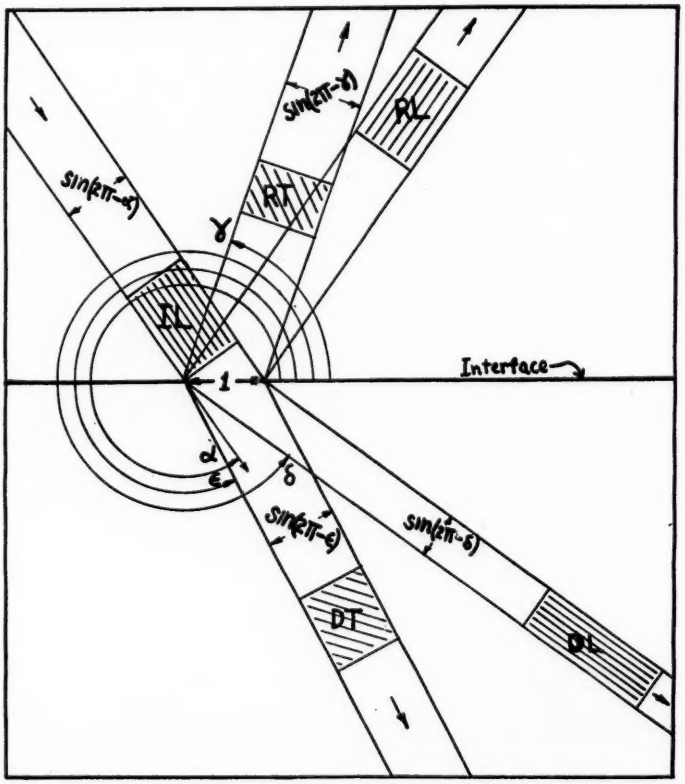

FIG. 7. Showing incident longitudinal (IL) wave tube and its division after two periods of oscillation into reflected longitudinal (RL), reflected transverse (RT), refracted longitudinal (DL), and refracted transverse (DT) waves. The length of each tube is one-half wave length. This figure illustrates part of the significance of Knott's energy equation.

But this is the energy in a tube of unit cross-section and of length $(\frac{1}{2})$ wave-length. To reduce this to the compartments shown in Fig. 7,

we have merely to multiply by the widths of the compartments. Thus,

$$\begin{aligned}\rho_1 a_1 \sin(2\pi - \alpha) u_{il0}^2 = {} & \rho_1 a_1 \sin(2\pi - \alpha) u_{rl0}^2 + \rho_1 b_1 \sin\gamma v_{rt0}^2 \\ & + \rho_2 a_2 \sin(2\pi - \delta) u_{dl0}^2 + \rho_2 b_2 \sin(2\pi - \epsilon) v_{dt0}^2\end{aligned} \tag{36}$$

where

(Incident longitudinal)

$$\left.\begin{aligned} u_{il} &= u_{il0}\cos\alpha(\exp)(2\pi i(t - (x\cos\alpha + y\sin\alpha)/a_1)/T) \\ v_{il} &= u_{il0}\sin\alpha(\exp)(2\pi i(t - (x\cos\alpha + y\sin\alpha)/a_1)/T)\end{aligned}\right\} \tag{37}$$

(Reflected longitudinal)

$$\left.\begin{aligned} u_{rl} &= u_{rl0}\cos\alpha(\exp)(2\pi i(t - (x\cos\alpha - y\sin\alpha)/a_1)/T) \\ v_{rl} &= -u_{rl0}\sin\alpha(\exp)(2\pi i(t - (x\cos\alpha - y\sin\alpha)/a_1)/T)\end{aligned}\right\} \tag{38}$$

(Reflected transverse)

$$\left.\begin{aligned} u_{rt} &= -v_{rt0}\sin\gamma(\exp)(2\pi i(t - (x\cos\gamma + y\sin\gamma)/b_1)/T) \\ v_{rt} &= v_{rt0}\cos\gamma(\exp)(2\pi i(t - (x\cos\gamma + y\sin\gamma)/b_1)/T)\end{aligned}\right\} \tag{39}$$

(Refracted longitudinal)

$$\left.\begin{aligned} u_{dl} &= u_{dl0}\cos\delta(\exp)(2\pi i(t - (x\cos\delta + y\sin\delta)/a_2)/T) \\ v_{dl} &= u_{dl0}\sin\delta(\exp)(2\pi i(t - (x\cos\delta + y\sin\delta)/a_2)/T)\end{aligned}\right\} \tag{40}$$

(Refracted transverse)

$$\left.\begin{aligned} u_{dt} &= -v_{dt0}\sin\epsilon(\exp)(2\pi i(t - (x\cos\epsilon + y\sin\epsilon)/b_2)/T) \\ v_{dt} &= v_{dt0}\cos\epsilon(\exp)(2\pi i(t - (x\cos\epsilon + y\sin\epsilon)/b_2)/T)\end{aligned}\right\} \tag{41}$$

In all the above, "real part of" is to be understood, and when quantities are squared, the real part is squared. Equation (36) is, except for a multiplicative factor, the same as Knott's energy equation. Thus Fig. 5 shows how Knott's equation is to be interpreted. The expression gives the partition of energy, and yet we must be careful in its use, because the five sets of infinite trains of plane waves imply infinite energies. As α increases, δ increases to 2π. When δ is near 2π, the width DL is very small, indicating that the refracted longitudinal energy is very small. In spite of this, the energy density in the refracted longitudinal wave is not small. Thus when $\delta = 2\pi$, although the incident disturbance contributes no energy to the refracted longi-

tudinal wave, that wave has a large energy density! This appears to be a physically impossible situation, and may be attributed to the fact that infinite trains of plane waves are themselves physically impossible.

CONSIDERATION OF NORMAL REFLECTION

Consider the simplest case, where $\alpha = 3\pi/2$ so that (37), (38), and (40) become

$$u_{il} = 0, \quad v_{il} = -u_{il_0}(\exp)(2\pi i(t + (y/a_1))/T) \tag{42}$$

$$\left.\begin{aligned} u_{rl} &= 0, \quad v_{rl} = u_{rl_0}(\exp)(2\pi i(t - (y/a_1))/T) \\ u_{dl} &= 0, \quad v_{dl} = -u_{dl_0}(\exp)(2\pi i(t + (y/a_2))/T) \end{aligned}\right\} \tag{43}$$

The conditions at the interface are

$$v_{il} + v_{rl} = v_{dl} \tag{44}$$

$$(2\mu_1 + \lambda_1)((\partial v_{il}/\partial y) + (\partial v_{rl}/\partial y)) = (2\mu_2 + \lambda_2)(\partial v_{dl}/\partial y). \tag{45}$$

Applying (42) and (43) to (44) and (45), we get

$$(u_{il_0} - u_{rl_0}) = u_{dl_0} \tag{46}$$

$$a_1\rho_1(u_{il_0} + u_{rl_0}) = a_2\rho_2 u_{dl_0}. \tag{47}$$

Solving, we get

$$u_{il_0} = \{(a_2\rho_2 + a_1\rho_1)/2a_1\rho_1\}u_{dl_0} \tag{48}$$

$$u_{rl_0} = \{(a_2\rho_2 - a_1\rho_1)/2a_1\rho_1\}u_{dl_0}. \tag{49}$$

By multiplying (46) and (47) together, we get the energy equation

$$\rho_1 a_1 u_{il_0}^2 = \rho_1 a_1 u_{rl_0}^2 + \rho_2 a_2 u_{dl_0}^2. \tag{50}$$

When $\rho_2 = 0$, we are considering reflection at a free surface. Then (45) gives

$$u_{rl_0} = -u_{il_0}. \tag{51}$$

When $\rho_2 = \infty$, (44) gives

$$u_{rl_0} = u_{il_0}. \tag{52}$$

Let Δ_i and Δ_r be the incident and reflected compressions, respectively. Then by (42) and (43)

$$\left.\begin{aligned} \Delta_i &= -(2\pi i/Ta_1)u_{il_0}(\exp)(2\pi i(t + (y/a_1))/T), \\ \Delta_r &= -(2\pi i/Ta_1)u_{rl_0}(\exp)(2\pi i(t - (y/a_1))/T). \end{aligned}\right\} \tag{53}$$

Comparing (53) with (42) and (43), we see that when Δ_i and Δ_r have the same phase at $y=0$, that v_{il} and v_{rl} have opposite phases there. In other words, when v has a node, Δ has a loop, as when $\rho_2=\infty$. It is thus necessary to specify "compression" or "displacement" in referring to changes of phase.

When two waves travel in the same direction, "phase" is easily defined in terms of the relative positions of maxima. In the case of waves travelling in opposite directions, the concept is more complicated. The displacement wave is a vector wave, whereas the compression wave is not. Furthermore, if we had a transverse wave in the above problems, the reversal of the y-direction involved in the reflection would not reverse the direction of the displacement vector. Hence we have three types of cases, and we can make the definitions independently. However, since it is customary always to use positive amplitude factors in comparing phases, we adhere to this custom; but note that vector waves must still be looked at as vector fields, and that a longitudinal wave with a positive amplitude factor, travelling in the positive direction, is not simply the wave obtained by reversing the reference direction of a wave of positive amplitude, travelling in the negative direction.

Now it certainly appears that (48) and (49) offer a good solution to the problem. However, in view of our doubts expressed concerning Knott's results at critical incidence, let us ask if any other solution is possible. Assuming v_{il} as given by (42), consider

$$v_{rl}' = -u_{rl_0}'(\exp)(2\pi i(t+(y/a_1))/T) \qquad (43')$$

$$v_{dl}' = u_{dl_0}'(\exp)(2\pi i(t-(y/a_2))/T). \qquad (43'')$$

Can u_{rl0}' and u_{dl0}' be chosen to satisfy (44) and (45)?

$$-u_{il_0}-u_{rl_0}' = u_{dl_0}'$$

$$-u_{il_0}-u_{rl_0}' = -\frac{\rho_2 a_2}{\rho_1 a_1}u_{dl_0}'.$$

These imply $u_{dl0}'=0$ and $u_{il0}'=-u_{rl0}'$. That this is *a solution* for the problem as stated, is evident, and its physical significance is also clear. Try the v_{il}, v_{rl}, v_{dl0}' combination. Then we have

$$-u_{il_0}+u_{rl_0} = u_{dl_0}'$$

$$-u_{il_0}-u_{rl_0} = -\frac{\rho_2 a_2}{\rho_1 a_1}u_{dl_0}'.$$

So

$$u_{il_0} = \{(\rho_2 a_2 - \rho_1 a_1)/2\rho_1 a_1\} u_{dl_0}'$$
$$u_{rl_0} = \{(\rho_2 a_2 + \rho_1 a_1)2/\rho_1 a_1\} u_{dl_0}'.$$

Here also we have a solution of the problem, and evidently the problem has infinitely many possible solutions.

Whenever we have such a result, we can always look for further conditions not previously used. The particular further assumptions are, that the *rl and dl waves must move away from the interface.* Now this is a quite natural assumption to make, and may perhaps be justified by the following consideration. Consider the flow of energy. It is only for the case where the *rl* and *dl* waves travel away from the interface that the energy conservation has a physical meaning. In the present case, the energy flowing into the sides of the tubes previously considered, is certainly equal to that flowing out, even at the interface, on account of symmetry.

BOUNDARY PROBLEMS

There are, involved in this study, some general properties of the differential equations that we should know.[4] The equation of wave motion

$$(1/v)^2(\partial^2\phi/\partial t^2) - \{(\partial^2\phi/\partial x^2) + (\partial^2\phi/\partial y^2) + (\partial^2\phi/\partial z^2)\} \equiv \Box\phi = 0 \quad (54)$$

has many solutions. Under certain circumstances, it is possible to supply "boundary conditions" which exclude all the solutions but one. Such a case arises when, for instance, we assign values of ϕ and of $\partial\phi/\partial t$ for $t=0$ that can be expanded in convergent power series in x, y, z, as

$$\phi(0, x, y, z) = \phi_0(x, y, z) = \phi_0 + \phi_{0x}'x + \phi_{0y}'y + \phi_{0z}'z + \cdots \quad (55)$$
$$(\partial\phi/\partial t)_{t=0} = \phi_1(x, y, z) = \phi_1 + \phi_{1x}'x + \phi_{1y}'y + \phi_{1z}'z + \cdots . \quad (56)$$

Consider then

$$\phi(x, y, z, t) = \phi_0(x, y, z) + \phi_1(x, y, z)t + (\phi_2/2!)t^2 + \cdots + (\phi_n/n!)t^n + \cdots \quad (57)$$

where

$$\phi_n(x, y, z) = (\partial^n\phi/\partial t^n)_{t=0}.$$

[4] An excellent reference on these matters is Hadamard's "Le Problem de Cauchy," Paris, 1932.

Note that $(\partial^2\phi/\partial t^2)_{t=0} = v^2(\nabla^2\phi)_{t=0} = v^2\nabla^2\phi_0$ and

$$(\partial^3\phi/\partial t^3)_{t=0} = (\partial^2(\partial\phi/\partial t)/\partial t^2)_{t=0} = \partial^2\phi_1/\partial t^2 = v^2\nabla^2\phi_1$$

(since $\partial\phi/\partial t$ is a solution of (54) whenever ϕ is, since $\Box(\partial\phi/\partial t) = \partial\Box\phi/\partial t = 0$). Proceeding in this way, we compute each $\phi_n(x, y, z)$ using only (54), (55), and (56). Thus (57), where it is convergent, forms an extension of the solution from $t=0$ out to $t=t$. It can be shown that (57) gives the *only* solution of (54) satisfying (55) and (56). Now $t=0$, is a hyperplane in the space-time (t, x, y, z), and the derivative $\partial\phi/\partial t$ is the normal derivative to this hyperplane. If the hyperplane is replaced by a more general hypersurface,

$$\sigma: \quad z_0(t, x, y, z) = \text{const.}, \tag{58}$$

then we might consider the data as given in σ. In such a case, we may make a change of variables

$$(t, x, y, z) \to (z_0, z_1, z_2, z_3). \tag{59}$$

Then (54) becomes

$$(\partial^2\phi/\partial z^2)\{(1/v)^2(\partial z_0/\partial t)^2 - (\partial z_0/\partial x)^2 - (\partial z_0/\partial y)^2 - (\partial z_0/\partial z)^2\}$$
$$+ \{\text{terms involving other partial derivatives of } \phi\} = 0. \tag{60}$$

Now observe that when

$$(1/v)^2(\partial z_0/\partial t)^2 - (\partial z_0/\partial x)^2 - (\partial z_0/\partial y)^2 - (\partial z_0/\partial z)^2 = 0 \tag{61}$$

we cannot use (60) to find the higher terms in

$$\phi_0(z_1, z_2, z_3) + \phi_1(z_1, z_2, z_3)z_0 + \cdots + \phi_n(z_1, z_2, z_3)z_0^n/n! + \cdots \tag{62}$$

the way we used (54) in (57). Hence, (61) represents the exceptional case, where the solution is either impossible or else is not unique. The hypersurface (58) satisfying (61) is called the *characteristic surface* for (54). It can be shown that the *characteristics* (short for "characteristic surfaces") can be identified with wave-fronts or surfaces of stationary phase.

The above material has been presented to show that in solving boundary value problems, special treatment must be given in case the data is given on a characteristic. For us, the surface where the data is given will be $y=0$, and the data we may then take to be

$$\begin{aligned} \phi(x, 0, z, t) &= \phi_0(x, z, t) \\ (\partial\phi/\partial y)_{y=0} &= \phi_1(x, z, t). \end{aligned} \tag{63}$$

Now evidently $y=$const. is not a characteristic, since (61) reduces to $-(\partial y/\partial y)^2=-1\neq 0$. It has been shown that a *sufficient condition*[5] that will insure the existence of a solution is, that ϕ_0 and ϕ_1 be analytic functions of x and z, and be regular functions of t, i.e., have derivatives with respect to t up to some order $n>2$. Consider, for example,

$$\phi(0, t) = ae^{ict} = \phi_0, \quad (\partial\phi/\partial y)_{y=0} = be^{ict} = \phi_1 \tag{64}$$

$$(1/v)^2(\partial^2\phi/\partial t^2) = \partial^2\phi/\partial y^2. \tag{65}$$

Then

$$\phi(y, t) = \phi(0, t) + \phi'(0, t)y + \phi''(0, t)y^2/2! + \cdots + \phi^{(n)}(0, t)y^n/n! + \cdots \tag{66}$$

where

$$\phi^{(2n)}(0, t) = (-1)^n(c/v)^{2n}\phi_0$$

$$\phi^{(2n+1)}(0, t) = (-1)^n(c/v)^{2n}\phi_1.$$

Hence

$$\begin{aligned}\phi(y, t) &= \phi_0\{1 - (cy/v)^2/2! + (cy/v)^4/4! - \cdots\} \\ &\quad + \phi_1\{(cy/v) - (cy/v)^3/3! + \cdots\}(v/c) \\ &= \phi_0 \cos(cy/v) + (v/c)\phi_1 \sin(cy/v) \\ &= \tfrac{1}{2}(\phi_0 + v\phi_1/ic)(\exp)(icy/v) \\ &\quad + (1/2)(\phi_0 - v\phi_1/ic)(\exp)(-icy/v).\end{aligned} \tag{67}$$

Thus the wave progresses in a negative y direction, when

$$ic\phi_0 = v\phi_1 \tag{68}$$

and in a positive y direction when

$$ic\phi_0 = -v\phi_1. \tag{69}$$

Thus we have a means of specifying conditions at the interface, so that the waves will travel outwards or inwards, according as we are dealing with transformed or with incident waves.

Now $v/c=vT/2\pi=\lambda/2\pi$ where λ is the wave-length. Hence conditions (68) and (69) involve the frequency or wave-length.

If we consider a "pulse," then, as is well known, this pulse may be analysed into its elementary harmonic components of various fre-

[5] Cf. Volterra, "Rivista di Mathematica," T. IV (1894), pp. 1–14. Hadamard, p. 348.

quencies; and when we know the intensity of each harmonic component, we know the "spectrum" of the pulse. Evidently, in treating pulses, one must assume either (68) or (69) to hold for all frequencies of their spectrum. We may also notice that if the phase is unaltered at the interface, then the shape of the pulse is unaltered. Referring to (48) and (49), we see that in general the *il* and *dl* waves have the same phase—this is true of both displacement and dilation. For the reflected wave, the case is altered. Supposing $a_2\rho_2 > a_1\rho_1$, (49) implies that u_{rl0} and u_{dl0} are of the same sign, and (43) implies that v_{rl} and v_{dl} are of opposite phase. However, none of the dilatations change phase. Hence, if the original pulse was a pure condensation, then the transformed pulses are also pure condensations. In case $a_2\rho_2 < a_1\rho_1$, it appears that v_{il}, v_{rl}, and v_{dl}, all have the same phase, but that a condensation in *il* is reflected as a rarefaction in *rl*. By combining several reflections from several layers, one can see roughly how a simple pulse of compression might be returned as an irregular oscillation. We have here at least a part of the basis of what seismic computers have called "character."

We shall continue this discussion in another paper.

For a more complete bibliography on this subject, see J. B. MacElwane's "Introduction to Theoretical Seismology," 1936, page 179. To this we wish to add reference to the papers on waves by K. Uller, especially his paper in *Deutsch. Phys. Gesell. Verh.* 16. pp. 835–849.

A NOTE ON THE SEISMIC-ELECTRIC EFFECT*

R. R. THOMPSON†

ABSTRACT

An experiment is described which apparently eliminates electrode surface effects as a cause of the seismic-electric effect. Evidently a volume variation of some electrical property or properties of the earth is necessary to explain the experimental results.

Since the publication of the patent and the first experimental results on the seismic-electric effect[1] there have appeared a number of papers concerning the cause and the nature of the effect as well as the possibilities of utilizing the effect in geophysical exploration.

A. Belluigi, in two articles,[2] has pointed out several important advantages in the utilization of the effect in recording seismic waves as compared to present types of seismographs. He has also proposed a circuit for seismic recording which employs separate current and potential electrodes and which greatly reduces any effects of polarization variations, etc., at the electrode surfaces. Two papers by Thyssen, Hummel and Rülke[3] give some very interesting experimental results. The first paper describes measurements made using electrodes of various materials in an electrolytic trough. Mechanical vibration of the trough resulted in varying the electro-chemical conditions at the surface of the electrodes and consequently in producing fluctuations in the current through the electrolytic cell. The authors suggest that this may be the explanation of the so-called seismic-electric effect.

In a second article, the same authors describe experiments with a sealed electrolytic cell composed of platinum electrodes in dilute sulphuric acid. The cell is vibrated mechanically by means of a lever driven by an eccentric wheel on an electric motor, and the resulting fluctuations in current through the cell are recorded. The results are ascribed to variations in the electrochemical polarization at the interfaces between the electrodes and the electrolyte, and there is evidence to show that these variations do not give a true picture of the motion of the cell.

While there can be no doubt that such electrode effects exist and

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[1] Numbered superscripts refer to the bibliography at the end of the article.

would act to change the current in such seismic-electric recording circuits as have been previously used, the question as to whether there is also an actual change in the resistivity of the earth under the influence of seismic waves has received little attention.

To obtain additional evidence on this question the experiment herein described was carried out.

Fig. 1 shows the arrangement of the seismic-electric recorder. Two current electrodes connected to a storage battery are used to send a

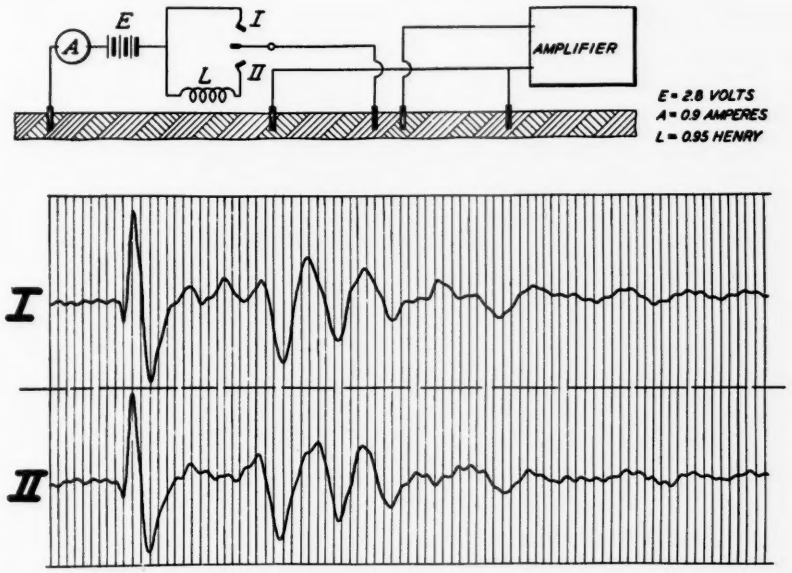

FIG. 1.

direct current through the earth; and three potential electrodes, spaced as shown, are connected to an amplifier having a high input impedance. This is similar to the circuit proposed by Belluigi.

The configuration of three potential electrodes reduces the noise from varying stray ground currents as has been explained in an earlier paper.[1]

The two outside potential electrodes are at equipotential points in the field set up by the current circuit so that the direct connection between these potential electrodes does not distort the field. The current circuit is provided with a switch so connected that for one position the battery is connected directly to the current electrodes, and

for the other position an inductance coil is inserted in series in the current circuit.

With the switch in position 1, a ground current of .90 amperes was obtained from a battery of 28 volts. Thus, in this case, the total impedance of the current circuit was about 30 ohms and may be considered a pure resistance for the frequencies involved in the seismic recording.

With the switch in position 2, a .95 henry choke having negligible D.C. resistance was inserted in series in the circuit. In this case the impedance around the circuit, at a frequency of say, 30 cycles per second, was about 180 ohms.

Using the set-up as shown, records were made of two successive dynamite shots of equal charges planted in the same hole. A standard pickup was used to check on the equality of the impulses from the two shots. Record I was taken with the current circuit switch in position 1, and record II with the switch in position 2. It will be observed that there is no appreciable difference in amplitude or character between the two records. It therefore appears that the effect can not be due to a change of current in the current circuit such as would result from localized variations at the electrode surfaces. If this were the case, record II should show a much smaller amplitude than record I, since the inductance loading in the current circuit increased the circuit impedance by a factor of at least six, in this case, and should have decreased the current variations proportionately. Moreover, if variations at the current electrode surfaces are not responsible for any appreciable amount of the effect, it appears highly improbable that variations at the potential electrode surfaces could be of importance since the current density across these surfaces is very low, and earlier experiments have indicated that the magnitude of the effect increases linearly with the current density.

It therefore seems that a variation of some electrical property throughout a relatively large volume of earth must be the cause of the effect. This might be either a variation in the specific resistivity of the earth or in the so-called volume polarization. However, the volume polarization at any point in the earth should be proportional to the current density at that point, and any change in this polarization due to elastic deformation of the earth would affect the observations in the same way as a change in the specific resistivity. In other words, the concept of volume polarization implies that across each element of volume through which current is flowing there exists a

polarization potential difference which is proportional to the current density. But across this same volume element there also exists the "ohmic" potential difference which is proportional to the product of the current density and the specific resistivity. Hence a change in volume polarization is indistinguishable from a change in specific resistivity so long as observations are confined to any sort of integration of the variation in total potential across these elements. The only apparent possibility of separating these effects lies in the use of A.C. energizing current which should eliminate volume polarization.

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GAMMA-RAY WELL-LOGGING*

LYNN G. HOWELL AND ALEX FROSCH†

ABSTRACT

Point-to-point measurements of radioactivity in bore holes were made with an ionization chamber. The correlation between the curves obtained and the electrical logs for the same holes led to the construction of a more rugged apparatus containing two Geiger counters, coupled separately to two amplifiers and two frequency meters on the surface of the ground. This instrument can be run continuously and logs taken in both cased and open holes. Correlation was obtained between two cased hole records taken several miles apart in West Texas. Remarkable correlation in many instances between radioactivity and electrical logs has been found in the Gulf Coast. The method seems to open up a broad field in cased hole well-logging.

INTRODUCTION

In the work done on gamma-ray well-logging there were two motivating points of interest. In the first place, there have been references in the literature to indicate that oil is fairly high in radioactive content. Thus, there was some hope that oil bearing formations might be distinguishable from other formations. As is well known, this is a very important problem in well-logging. In the second place, the present commercial electrical well-logging practice can not be used inside cased wells due to the shielding action of the casing. There are a number of old fields which were brought in before the advent of electrical logging and thus no logs of these cased wells can be obtained except through the casing. Again in present day gun perforating practice, a more accurate method of locating the gun in the oil bearing formation is needed. A possible solution is the use of a well-logging instrument capable of working inside the casing in conjunction with the gun. It is very difficult to hit upon a physical quantity which can be measured through the casing in the well. A possible exception is the measuring of temperature but the measurements in this case are, in general, conditioned; that is to say, the magnitudes of the changes measured usually depend on the difference of temperature between the mud and the formations. Thus, as the mud in the hole comes into thermal equilibrium with the formations, the temperature "kicks" tend to dis-

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appear. On the other hand there are inherent variations in the quantities of radioactive substances present in the earth's crust. Of the three types of rays associated with these substances, one, namely gamma radiation, is highly penetrating. From measurements of the intensity of the gamma-rays along the walls of a well it was thought that variations in the radioactivity of the formations could be obtained and that these measurements could be made either in an open or a cased hole, since the casing would not have a very large absorbing effect.

EXPERIMENTAL WORK

The first apparatus for making measurements was constructed in 1935 and consisted of a high-pressure ionization chamber made from $4\frac{1}{2}$ inch drill pipe. The ion chamber was about 4 feet long and 3 15/32 inches in diameter and was filled with nitrogen at a pressure of several hundred pounds per square inch. Nitrogen was used in preference to air because larger ionization currents are obtained with the same excitation. An electrometer tube placed in a compartment adjacent to the ionization chamber was used for detecting the ionization current. A conventional direct current amplifier circuit was used with a very sensitive galvanometer at the surface for making the readings. This set-up was very unsatisfactory because of cable leaks, drifts in the output current, etc.

A different type of circuit was next used with the electrometer tube. The set-up is shown in Fig. 1. The ionization chamber is shown in the lower part of the figure and was filled with nitrogen usually to a pressure of 500 pounds per square inch. The outside electrode is an insulated 1/16 inch thick aluminum case held at a potential difference of 135 volts with respect to ground. The central electrode is a wire stretched between two amber insulators. This arrangement gives a "guard ring" effect, since there is very little voltage across the amber insulators. The central electrode is connected directly to the grid of the electrometer tube, type D-96475. The grid of the tube is grounded for an instant every 3 seconds by means of clock work and thus pulses spaced at intervals of 3 seconds are generated. The magnitude of a pulse is proportional to the voltage built up on the central electrode and this in turn is proportional to the ionization current. The pulse is amplified by means of the amplifier shown at the surface of the ground, and the size of the amplified pulse is read on the galvanometer. This system gave much more satisfactory results in that an alternating current amplifier was used and therefore drift troubles were eliminated.

Two curves are shown in Fig. 2 taken in the producing sections of two Gulf Coast wells, both holes being open. Readings were taken from point to point, of the order of ten readings of the pulse size being taken

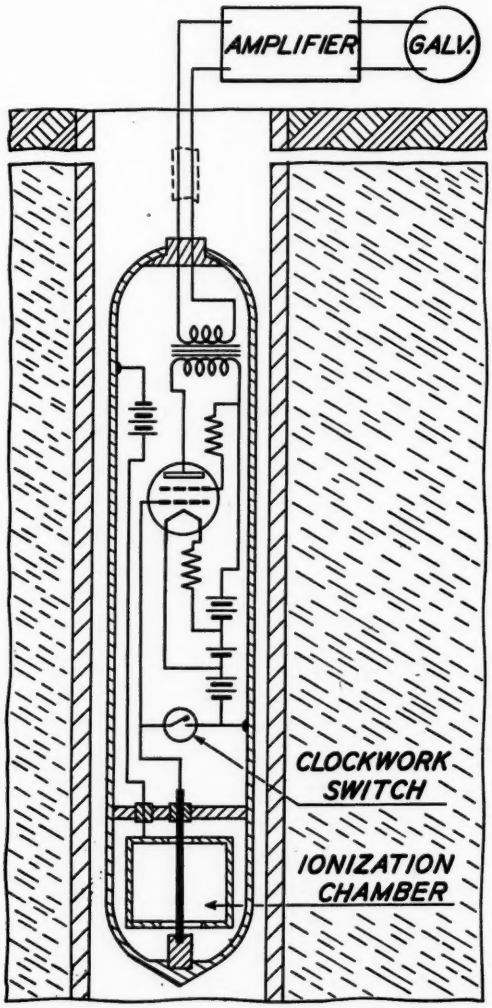

FIG. 1. Ionization chamber apparatus.

at each point while the chamber was held stationary. These readings are plotted against depth and the curves are compared to the conventional electrical log showing the potential and the resistivity. It will

be noticed that there are several pronounced "lows" on the radioactivity logs which correspond to pronounced "highs" on the electrical logs.

With these encouraging results it was thought worthwhile to work on the development of an apparatus which could be used in a practical way. It seemed important to eliminate the vacuum tube, which is inclined to be microphonic in a moving chamber, and thus to be able to record continuously as the chamber is moved. Geiger counters,[1] which are fairly rugged, were therefore installed in a new chamber.

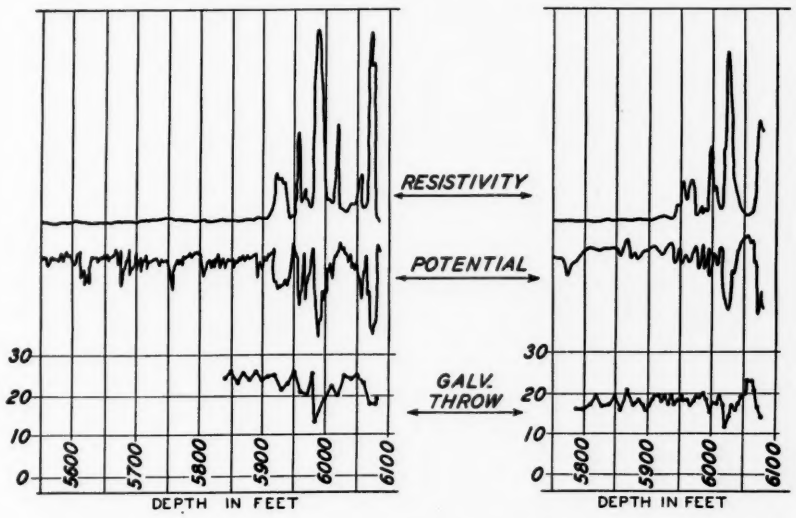

FIG. 2. Comparison of ionization chamber data with electrical logs in two Gulf Coast wells.

Geiger counters, of course, give discharge pulses as individual secondary particles (released by the gamma-rays) traverse the counter. They require a different type of circuit and we were able to hit upon a much more satisfactory set-up requiring no vacuum tubes in the chamber in the hole. The new arrangement is shown in Fig. 3. The Geiger counters, designed by G. L. Locher, are sealed in glass, the copper anodes being 18 inches long and $2\frac{1}{8}$ inches in diameter. The

[1] Some work has been done in Russia by means of Geiger counters but no very practical method has been obtained. Cf. V. A. Spah, *Comptes Rendus (Dohlady) de l'Académie des Sciences de l'URSS*, p. 109, Vol. 16 (1937).

distance between centers of the counters is about two feet. The counters are coupled through low-impedance-secondary transformers, to separate alternating current amplifiers on the surface. The pulses

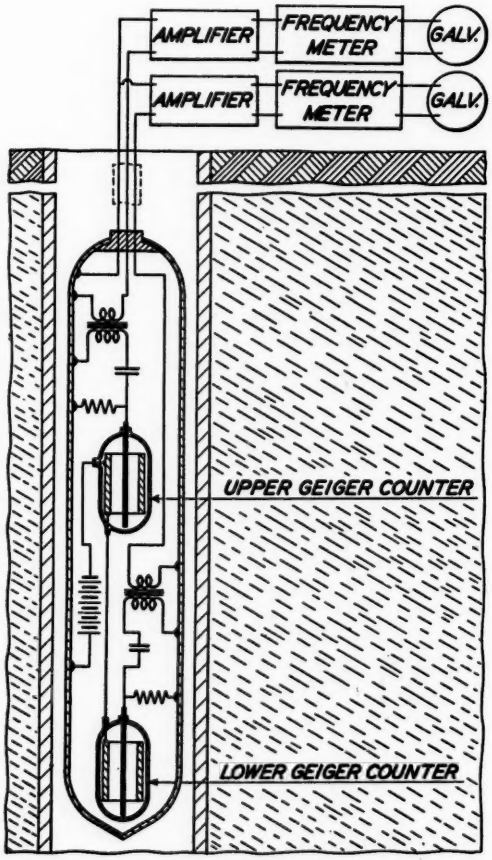

FIG. 3. Geiger counter apparatus.

caused by secondary particles in the Geiger counters are thus amplified and transmitted to separate thyratron controlled frequency meters, the output currents of which are proportional to the average rates of production of the pulses. Since these pulses occur at random, the output current of the frequency meter is continually changing, even with the same source of radiation. This current is smoothed out to some extent by using a tank circuit in the frequency meter contain-

ing a large condenser across a large resistance, the final arrangement being 12 micro-farads across 1 megohm. Due to these random variations it was thought advisable to use two counters in order that chance "highs" and "lows" might be ruled out in many instances by comparing one trace against the other. The galvanometer deflections were recorded continuously on photographic paper by means of the Humble experimental well-logging truck apparatus.

Fig. 4 shows logs taken in two cased holes several miles apart in a West Texas field. The cement plugs in the casing did not allow the

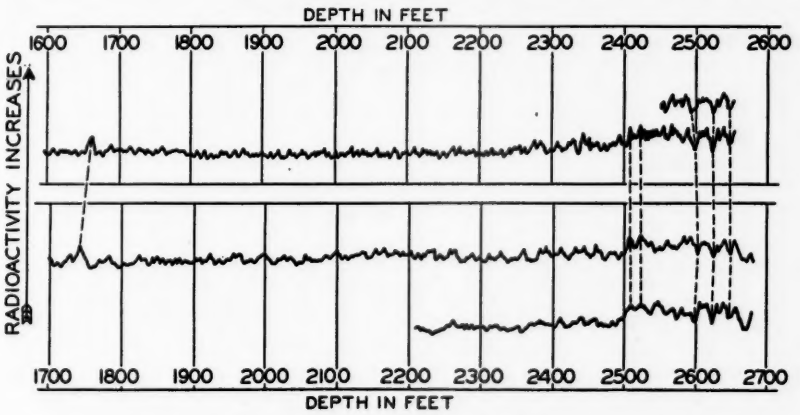

FIG. 4. Comparison of gamma-ray logs in two cased wells in a West Texas field.

counters to be dropped to the bottom in the producing horizon. Also some noise was encountered on the trace of one counter, and therefore, only the trace of the other together with short repeat runs is shown. It will be noticed that the correlation between the two logs shows a difference of about 100 feet in depth for corresponding formations in the wells. There is a pronounced increase in the general radioactivity at about 2400 feet in the upper log which is seen at about 2500 feet in the lower trace. Also several peaks and valleys follow which can be traced across. It might be mentioned in connection with the low radioactivities encountered in the salt and anhydrite section in these wells that Mott-Smith and Howell[2] found the salt in the Grand Saline salt mine extremely low in radioactive content.

Figs. 5 and 6 show logs made in two open holes in the Gulf Coast. A more sensitive galvanometer is used on one trace of the

[2] Mott-Smith and Howell, *Physical Review*, Vol. 44, p. 4 (1933).

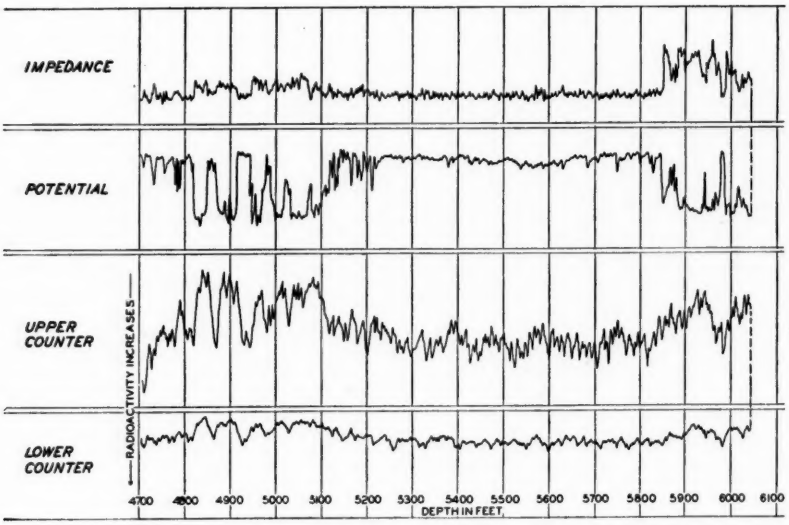

FIG. 5. Comparison of gamma-ray log with electrical log in an open hole in the Gulf Coast.

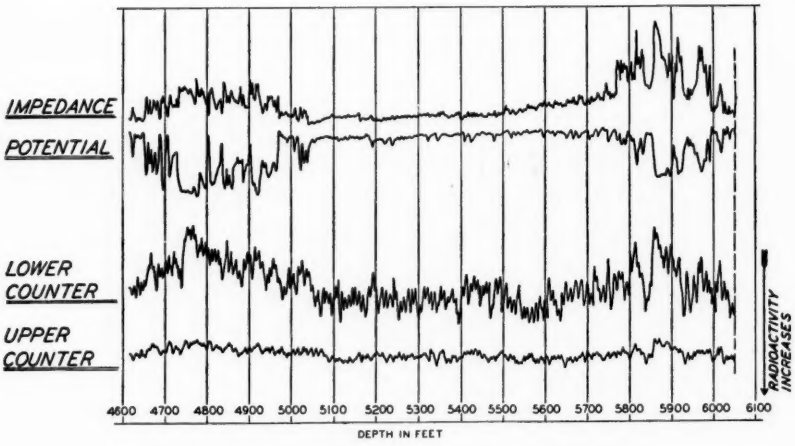

FIG. 6. Comparison of gamma-ray log with electrical log in an open hole in the Gulf Coast.

gamma-ray log; this trace gives changes which are more nearly comparable with the electrical log, but necessarily at the same time gives amplified chance variations. These runs were made at a speed of the

order of 25 feet per minute. It is very remarkable to see the correlation between the radioactive lows and the electrical highs. The upper water sands, as shown by the electrical logs, stand out very clearly on the gamma-ray logs, as also do the producing sands at the bottoms of the holes. There is a long shale section in the middle portion between the two sand bodies which shows as an electrical low and as a radioactive high.

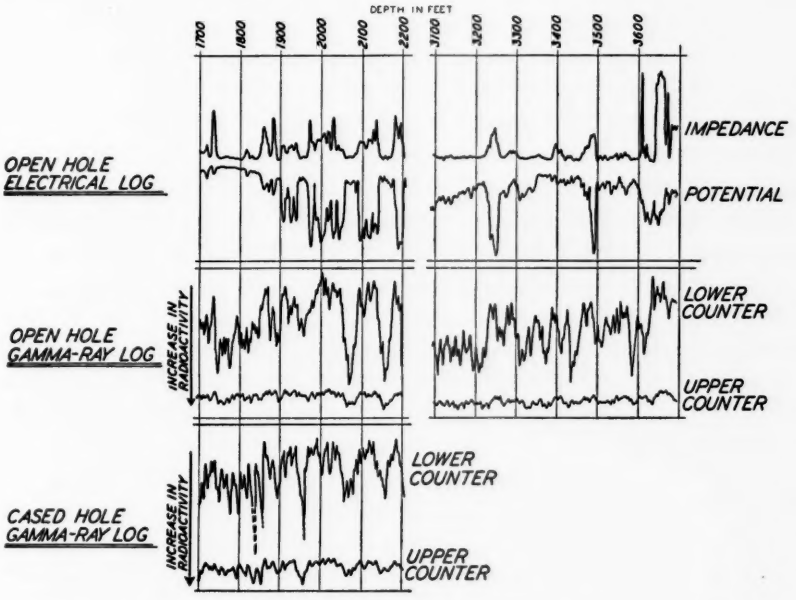

FIG. 7. Comparison of open hole electrical log, open hole gamma-ray log and cased hole gamma-ray log in a Gulf Coast well.

Fig. 7 shows another set of logs made in a Gulf Coast well. The top log shows the conventional electrical traces; the middle log, the open hole gamma-ray traces; and the bottom log, the cased hole gamma-ray traces in the upper sands. The correlation between gamma-ray and electrical logs in the upper sands is very striking. There are some extra "kicks" on the gamma-ray trace in the producing section and yet the large electrical peaks for the most part are prominent as radioactive "lows." The record in the cased hole is marred to some extent by noise, some of the worst bursts being dotted in. However, the three prominent sands at 2000, 2100 and 2200 feet

show very clearly. Although there is perhaps a change in sensitivity between the two logs, a qualitative idea of the absorption by the casing and environs can be obtained by noting the difference in size of the peaks of the two records.

CONCLUSION

An instrument about 12 feet long and $3\frac{1}{2}$ inches in diameter, containing two Geiger counters, has been developed for the purpose of detecting radioactivities of formations in bore holes. Logs can be taken at a speed of the order of 25 feet per minute. Characteristic variations of radioactivity have been measured in both cased and open holes; in fact, all measurements are made through at least one thickness of pipe since the Geiger counters are enclosed in a steel case. Logs have been taken in both West Texas and the Gulf Coast, changes in which logs can be correlated with geology. A most interesting and surprising factor is the similarity in behavior in many instances between such widely different physical properties as those measured by electrical and radioactivity logs. No evidence of high radioactivity in oil sands has been found; but, on the contrary, oil sands like other sands have been found to possess low radioactivity. In some instances the high radioactivity occurring at the bottom of a sand might indicate the settling out of heavy radioactive minerals. In conclusion, it may be said that for obtaining logs which can be correlated with geological formations, the radioactivity method offers, for the first time, a general method for working inside the casing. It is yet too early to evaluate the eventual utility of the method.

IMPROVEMENTS IN SEISMIC PROSPECTING IN 1938*

JOSEPH L. ADLER†

Improvements in reflection seismographs have been made during the past two or three years which have made it possible to use the method in areas previously considered unworkable. But these are not developments of the *current* year. The developments were worked out in regular seismograph country in the recent past, and the noteworthy thing for this year is that they have now been applied successfully for the first time to areas which seismologists abandoned four or five years ago as unworkable.

The outstanding feature which makes these areas difficult is a cover of unconsolidated rock of very irregular thickness overlying rocks having high velocity and irregular topography. The irregularities run into hundreds of feet. Specific examples in this country are the drift-covered Lower Peninsula of Michigan and parts of Ohio, and the irregularly filled valleys of western Kentucky and southern Indiana. Another difficult type of country in which successful seismograph work has recently been done, is terrain in which a great thickness of limestones or other hard rocks lies at or very near the surface of the ground and is underlain by softer rocks. The outstanding example of such an area in the United States is a large part of West Texas. Similar conditions in foreign countries are, of course, numerous.

The improvements which make this type of terrain workable now are 100% automatic volume control and compounding of geophone energy. By the latter, I mean feeding the energy from one group of geophones into two or more galvanometers and likewise, simultaneously feeding the energy from two or more groups of geophones into each galvanometer. This type of circuit, in addition to being more effective in reducing ground roll than mere multiple geophones, tends to line up ragged reflections which might otherwise be undetectable. This type of circuit is not entirely new; it is the application to these previously abandoned regions that is new.

Recent instrumental research has mostly been along the lines above indicated. There are two schools of thought in regard to compounding

* Paper read at the Geophysical Section of the A.I.M.E., New York, Feb. 15, 1939.

† Independent Exploration Co., Houston, Texas.

of geophone signals. The one school holds that the compounding should be strictly limited to each pair of adjacent galvanometers, in order to reduce to a minimum the danger of manufacturing an apparent but false reflection as a result of an isolated disturbance moving only one or two geophones. The other school believes in developing a mixing panel by means of which the operator may at will feed the energy from any group of geophones to all the galvanometers. The inherent danger in this type of instrument becomes obvious when one considers that by feeding the energy equally from all geophones to all galvanometers every impulse on the record would have the appearance of a reflection. This danger is somewhat offset by the fact that many impulses which are not reflections would be eliminated almost entirely from the record by such a circuit.

Of course, no operator would go the extreme of mixing suggested above, but the point I wish to make is that it would be dangerous to trust the most conservative operator in the field with such an instrument, because in a desperate effort to get reflections in a difficult area, he would undoubtedly approach too closely the extreme case mentioned above, manufacturing reflections which do not exist.

Other factors which have received much attention during the last year deal mainly with field operations. There has been continued experimentation with the distribution and spacing of geophones. Distribution to give practically continuous sub-surface coverage ("continuous profiling") has been used more and more in certain areas of small structural relief. There has also been some experimentation with the arrangement of geophone groups in various geometrical patterns such as small squares, diamonds, and triangles instead of in long straight lines, large crosses, or arcs as had been done previously. While the results of these experiments are not available, it is reported that some apparently unexplainable effects have been obtained.

In the spacing of geophones there has fortunately been a general reversion to common-sense. For several years many operators attempted to improve the appearance of the reflections on their records by placing the geophones closer together, sometimes as close as 20 feet between the effective mid-point of each multiple geophone group, giving in all only about 80 to 100 feet of wave-front coverage for the entire spread. The fallacy therein is obvious: innumerable experiments show that the number of random non-reflection impulses which affect 100 feet of surface is several times as great as the number of such stray impulses which will affect 500 feet of surface. In

addition, thereto, with 100 feet of coverage the difference of arrival time of refracted waves at the nearest and farthest geophones is too nearly the same as the arrival time difference for reflected waves. It becomes impossible to distinguish the two in the case of the shallower reflections. Most operators are now abandoning these close spacings.

In order to make wide coverage an economic possibility there has been a tendency to increase the number of traces on the oscillographs so that more coverage could be obtained at one set-up. Whereas, two years ago most oscillographs recorded on from four to six traces now most of them use from eight to twelve. One company is actually using twenty and it is reported on reliable authority that one research department is experimenting with forty. Of course this can be carried to an absurdity, the field crew becoming so overburdened with geophones and cables to be set out and amplifiers to be adjusted that they could shoot two set-ups with x traces faster than they could shoot one with $2x$ traces. However, x is still an unknown quantity.

Where a very large number of traces are used the coverage does not increase proportionately. The geophones are placed closer together in that case so that the coverage is more detailed. It is impossible to increase the actual coverage in many areas to more than about 1000 feet of surface wave, because the difference in wave path from the first to last geophone introduces changes in wave character that prevent tracing a reflection clear across the record with confidence that one is following the same phase throughout. I have seen records having only 750 feet of coverage in which this trouble appeared and on the other hand I have seen records with 1500 feet of coverage where it did not appear. However, changing of phase in broad coverage records may occur without being apparent; so broad coverage from a single shot-point contains latent danger of serious error. It is a danger which is inherent in certain forms of continuous profiling also.

The movement of American seismograph crews continues away from the United States. Particularly marked is the movement into the troubled Eastern Hemisphere. If a major war should develop in Europe and Asia it might prove a terrific blow to American seismograph men. On the other hand, if the seemingly impossible is accomplished and the Old World is ever really pacified without a general war there should shortly thereafter be a petroleum wildcatting boom and therefore a seismograph boom all over that hemisphere.

GEOMAGNETIC EXPLORATION IN 1938*

NOEL H. STEARN†

One result of the intense experimental activity in geophysics during the last decade has been the establishment of approximate boundaries to the provinces of applicability of the different geophysical methods. Generally speaking, the oil industry has turned to the seismograph except for certain limited regions and specific problems. The mining industry has turned more to electrical devices except where magnetic methods have demonstrated a specific aptitude.

As experience brings into sharper focus the relative functions of the different geophysical methods, it becomes interestingly clear that the geomagnetic method is taking over the function of scouting. The winning of western America from unknown wilderness in such a short time can be partly credited to the ability of its famous scouts. With geomagnetics as the Kit Carson or Pawnee Bill of geophysics, the wilderness of geological problems which confronts the explorer for natural resources should perhaps parallel the history of western America.

Reports of geomagnetic activities for the year 1938 add much evidence that the geomagnetic method has become trail breaker for other methods. For example, Mark C. Malamphy, S. F. Kelly, J. J. Jakosky, W. M. Barret, Hans Lundberg, and others, report the use of magnetic surveys as preliminary to surveys with other methods.

In South Carolina, Malamphy used magnetics in connection with resistivity, Ground Comparator, and spontaneous polarization methods for outlining old and discovering new ore bodies for the Haile Gold Mines.

Raleigh P. Trimble has reported the use of magnetics as a preliminary survey to electrical work and also as directional to extensive seismograph work in the San Joaquin Valley of California.

In addition to the specific trail breaking duties of the "scout of geophysics," the magnetic method has taken over general scouting duties, as exemplified by extensive regional surveys such as the one undertaken by the Missouri Geological Survey. Missouri's magnetic survey is aimed at the problem of outlining major regional structural

* Paper read at the Geophysical Section of the A.I.M.E., New York, Feb. 15, 1939.
† W. C. McBride, Inc., St. Louis, Mo.

features throughout the state. H. S. McQueen, Assistant State Geologist of Missouri, reports that during 1938 approximately 6,100 square miles were covered, bringing to a total of 25,000 square miles the area magnetically surveyed in the state. A recent report on "The Geology of Northwestern Missouri," by H. S. McQueen and F. C. Greene, contains a map showing variations in vertical magnetic intensity over the entire northwest quarter of the state.

In Michigan, Frank Pardee last year reported the beginning of an extensive magnetic survey in the copper district of the Upper Peninsula. Between Painesdale and the Ontonagon area a deep overburden of glacial drift has in the past baffled exploration. A crew was sent in under the direction of Carl Lamey to determine, if possible, the trend of the lodes in that area, and to attempt to locate the fault zones which cross the lodes and which are unfavorable for copper mining. A very detailed survey is being conducted, with the hope of completion in 1940. Work was also started in the iron country in Dickinson County.

In the Highwood Mountain area of Montana the United States Geological Survey is attempting by magnetic studies to detect possible laccolith feeders.

South Africa, according to a report by Rudolf Krahmann, has seen interesting developments during 1938. The magnetic survey of the properties of the West Witwatersrand Areas, Ltd., between Randfontein and Potchefstroom has now embraced over 150,000 observations of vertical and horizontal intensity along more than 2,000 miles of traverse. The subsequent drilling of 25 bore-holes has determined the presence of the predicted gold-bearing conglomerates over a distance of 29 miles.

In the Orange Free State, southwest of the Witwatersrand, several companies initiated magnetic surveys during 1938, designed to cover a total area of approximately 1,800 square miles.

F. Bahnemann, of West Witwatersrand Areas, Ltd., and G. G. Wiles, of the University of the Witwatersrand, are now investigating the effects of elastic deformations on magnetization, and a detailed report is in preparation which will supplement a preliminary paper published in 1938.[1]

Outside the city of Cape Town a new magnetic observatory is being established by A. Ogg, and under his supervision K. W. Simpson is establishing about 20 magnetic base stations throughout the Union,

[1] Bahnemann, Fritz, Die Magnetisierung geologischer Koerper, *Beitr. Angew. Geophysik* (7) (1938), pp. 281–284.

in order to observe the secular variations of the vertical and horizontal components.

The scouting function of geomagnetics has led it into the Far North also. C. O. Swanson reports the use of magnetic methods near Lake Athabasca where some interesting features in connection with the ordinary dip needle were encountered. Due to the steep inclination of the earth's magnetic field, the dip needle becomes progressively more sensitive northward so that in the latitudes of Lake Athabasca temperature effects, generally considered negligible in the Lake Superior Region for example, become very marked. The effects of magnetic storms are also greatly accentuated.

The Lake Superior Region remains the outstanding area for the direct application of geomagnetic methods of exploration to the mining industry. There, in addition to continued use of the ordinary dip needle, attention is being focused on careful resurveys with more sensitive magnetic instruments of areas where the ordinary dip needle has proven inadequate. A. E. Walker reports considerable work of this nature on the Cuyuna Range in Minnesota, done by Louis Knudsen with the Hotchkiss Superdip. The Cuyuna Range is buried under a thick glacial overburden, and lands there have no especial value unless it can be shown by geomagnetics that there is a possibility of finding iron ore.

In the structurally complex Iron River district of Michigan, Walker also reports success in tracing the iron formation by means of local surveys with sensitive instruments in areas where the magnetic anomalies are too weak to be detected by the ordinary dip needle.

During 1938 magnetic activity in the oil industry has continued at about the same pace to which it was adjusted after the approximate limitations of the applicability of the method had been outlined both geographically and geologically. California, the Mid-Continent, the Gulf Coast, and South Texas have all continued to yield magnetic results of interest. Mention has already been made of the use of magnetic work to point electrical and seismic exploration in California.

In the Mid-Continent the recent Illinois oil boom has brought to attention an area where geomagnetic methods may be called on with greater insistence to perform their scouting functions. The contiguity of Western Illinois to the Ozark Uplift where the Missouri Geological Survey has already established the usability of the magnetic method for indicating regional structure, leads to the conclusion that Western Illinois may also have its major regional features outlined magneti-

cally. And the recent discovery of oil in the Devonian limestones at Sandoval will perhaps give the requisite incentive for trying to outline the deeper structural features for subsequent detail work by other methods.

During the year 1938 an intense leasing campaign developed in the Forest City Basin, embracing Northwest Missouri, Southwest Iowa, Southeast Nebraska, and Northeast Kansas. That part of Missouri which lies in the basin has already been covered by a magnetic survey. But major oil companies are moving in field parties to cover the other areas, notably Northeastern Kansas.

Perhaps the most active area for the local use of geomagnetics in the oil industry lies in South Texas, as a result of reports crediting the method with assisting in the discovery of the Sinton, Plymouth, Heyser, Sweden, and Hoffman Pools. As was the case last year, however, thought on the success of the magnetic method in South Texas is sharply divided among three groups. First, there are those who "believe" in magnetics, pointing to the fact that credit for the discovery of several oil pools has been partly given to magnetic surveys. Second, there are those who "disbelieve," pointing to the fact that the data supporting magnetic applicability in the area are purely empirical, that no reasonable theoretical background for the interpretation of magnetic anomalies in this region has been articulated by the proponents of the method, and that statistically the presence of oil pools in indirect association with magnetic anomalies could be purely fortuitous. Third, there are those who, recognizing the force of the empirical data submitted by the proponents and acknowledging the validity of the arguments advanced by the opponents, have decided to withhold judgment in the matter.

The situation in South Texas emphasizes the general status of the application of geomagnetics to exploration, and hints at an explanation of why the method has been assigned to the scouting department of geophysics. Ever since the pioneer work was done in geomagnetics, the technique of measurement has far outstripped the technique of interpretation. Anomalies could easily and quickly be measured and reported, but in many cases other methods had to be called on to determine the meaning of the anomalies.

Many difficulties have arisen in connection with the application of geomagnetics to exploration, difficulties begging the assistance of physicists, and geologists, and geophysicists. Some of the difficulties are so vague that as yet they have not reached that stage of definite-

ness where they can be regarded as problems. But surely advancement is being made toward the crystallization of these difficulties into problems, and the solution of the problems. And surely an exchange of experiences among those active in the actual application of magnetic methods would serve to speed up the advancement.

Perhaps nearest the economic front at this time is the problem of an adequate articulation of the sound scientific theory behind interpreting the anomalies found in South Texas. Such an articulation would lend such immeasurable weight to the empirical data presented that it would seem to justify the time involved even for the busiest operators. Perhaps it is not hoping too much to look forward during the ensuing year to such an articulation.

A REVIEW OF PROGRESS IN GEOPHYSICAL INSTRUMENTS FOR THE YEAR 1938*

SHELLEY KRASNOW†

Any account of progress in a rapidly changing field will necessarily be out of date. This holds with special emphasis in geophysics. Equipment that will be described as new might have been in successful use for perhaps two or three years. The date of its release rather than of its appearance, however, must be used. Similarly, there have been improvements during the past year which show exceptional promise. Discussion of these however, must be deferred until their formal release.

The past year has seen not only more or less minor improvements in equipment, those arising out of routine laboratory research, but has also seen the announcement of instruments new in their entirety. Prospecting techniques have changed somewhat and these changes have brought necessary instrument changes with them. The increasing difficulty of the problems offered to the seismic prospector have required more perfect instruments; the increasing interest in gravity methods has resulted in the development of a number of new types designed to place this method within economic reach; the shift toward the new electrical methods and soil analysis methods has brought new instruments in these fields. There have also been developments maturing out of long research, and apparently not related to any pressing requirement.

In seismic apparatus, we find little change in detectors. The reluctance type of magnetic detector still appears to hold favor, and more or less minor improvements have been made in the damping, and reduction of size of these units. The design has also been altered to provide for a greater voltage increase per unit motion of the detector. There has been what might be termed a quantitative rather than a qualitative change in detectors. Whereas in early work six detectors would be used in a single set-up, at present it is not at all unusual to find perhaps 60 for each shot. The practice of using multiple geophones in series together with 12 or more traces may easily involve at least the number of detectors stated.

* Paper read at the Geophysical Section of the A.I.M.E., New York, Feb. 15, 1939.
† Geophysical Instrument Co., Washington, D. C.

The carbon microphone detector, which played so important a part in early refraction work, has been found well adapted to shallow work in connection with civil engineering projects. The sensitivity and stability of this instrument have been markedly improved during the past year.

A good deal of work has been done on automatic volume control systems. While details of the individual systems have not been made public, it is understood that a number of reliable types, all working on somewhat different principles, are in use. This improvement alone has made possible seismic work in areas where it was previously deemed impossible. The practice has also grown up of superposing a portion of the response from a detector on the next succeeding trace, and in some cases on all the other traces. There have been improvements also in the elements of construction of amplifier units, among which may be mentioned a new type of resistor sealed in an evacuated glass tube, and a high gain amplifier tube.

The number of traces has grown from the six customarily used in the early days of seismic work to 10 or 12, with a growing tendency toward the use of 20 or 24. It is said that one company is even experimenting with a 40 trace unit. Aside from the necessarily increased number of elements required for the increase in number of traces, there have been only more or less minor improvements in galvanometers. Among these may be mentioned the development of a multi-element bifilar type; also the development of a very compact and highly sensitive unit, suitable for combining for any desired number of traces.

The greater number of detectors has made the handling of field cables a rather embarrassing problem. Some users have taken to the employment of power operated reels to drag in the cables after finishing operations at one site. The practice has also grown up of using a low cost shot wire, and abandoning this rather than bearing the cost of reeling and unreeling.

In gravity measuring apparatus, we find the development of a number of instruments. Of those announced may be mentioned that due to Mott-Smith, employing an astatic system made entirely of quartz, with all joints fused. This is in effect a pendulum on a horizontal fibre with the addition of what is termed a "labilizing spring." This system, in common with all other successful types employs an elaborate temperature control system. Another gravimeter due to Hoyt, and in successful use for some years, employs a helical spring

with a mass at the end. This spring is hung vertically, and any increase in the force on the mass will result in a partial uncoiling of the spring. The small rotations due to small changes in gravity are measured by a new optical system employing multiple reflections. Electromagnetic damping and an elaborate system for arresting the spring are further features of construction. This instrument is somewhat sensitive to magnetic forces and must be oriented in the earth's magnetic field. Precisions as great as five parts in 100 million have been claimed for this instrument. Another instrument due to Thyssen employs an astatic system made up of a horizontal lever, a weight and an astatizing spring. Still another type makes use of a pair of vessels containing liquid with an interconnecting tube. The system is pivoted on a knife edge, and made stable by the use of a spring exerting a vertical force on one of the vessels. Any slight extension of the spring will bring its associated vessel slightly below the level of the other, causing liquid to flow into it. It can easily be seen that it is possible to bring such a system very near the point of instability. Still another instrument due to Graf employs a mass at the end of a vertically suspended spring; the distance between the mass and a fixed element below it being measured to within very close limits by an electrical system. The change in distance is indicated on a galvanometer mounted on top of the apparatus. There have been further improvements in an instrument due to Wright. This employs a torsion spring which is at theoretical zero stress when the instrument is not being read. Improvements in it have included changes in its temperature control system, decrease in its weight, and improvements in facility of operation.

Improvements have been made by Haalk in a gravity apparatus in which a liquid column is balanced against a gas pressure.

An instrument described in 1937 and due to Lindblad, employs a mass supported by curved leaf springs. A set of condenser plates attached to the mass and to the support serve to indicate the "null" position. An additional and similar set of condenser plates are connected to a source of variable E. M. F. In operation the position of the weight is brought to a "null" position by varying the E. M. F. across the second set of plates. The E. M. F. required to do this is a measure of the gravitational force.

In practically all the instruments mentioned and in some older types not mentioned here, there has been a strong effort to improve the temperature control system and to reduce the "zero drift" of

the instrument. There have been improvements in auxiliary equipment for gravity apparatus, among them a new type of mounting in a truck, permitting the instrument to be read without removing from the truck. In common practice a set of legs are lowered to the ground through openings in the truck floor and the instrument allowed to come to rest, supported in this way. This has the advantage of saving the instrument from the shocks incident to the removal from, and replacement in, the truck, and in further protecting the instrument from wind and sudden temperature change while being observed. A considerable amount of work is now being done over shallow bodies of water. This has necessitated the construction of supports for instruments, built up from the bottom of the body of water. Another type of apparatus allows the lowering of the instrument to the bottom of the body of water, in a suitable chamber.

At least two commercial gravimeters to be sold "off the shelf," so to speak, are being offered. Although commercial instruments have been available previously, the writer is not aware that these have been of the construction and precision necessary for modern prospecting work.

A considerable number of new electrical systems have been announced, it being common knowledge that the diversity of electrical systems is considerably greater than for other types. It will be difficult to evaluate the systems without seeing more of the actual results obtained with then. Of those which have had successful field use may be mentioned the modification of the Broughton-Edge system due to Watson. By employing an auxiliary set of resistances and condensers an additional set of values is obtained for the balance condition. This gives another set of equations, the solution of which gives the result free of electrode resistances. By adjusting the values of one of the auxiliary impedances, the solution of the equations may be made relatively simple.

There have been developments also in electrical systems employing transients. Basically the systems cause a square front pulse of current to be sent into the ground. The transients existing at a pair of potential electrodes due to this pulse are observed. The most commonly used method of generating the pulse involves the use of a Thyratron, which serves as a very effective switch. The transient may be observed on the screen of a cathode-ray oscillograph, or better, photographed. A modification of this technique employs a periodic

set of impulses in the current circuit, at a frequency of about 50 cycles. Instead of observing the transient, an attempt is made to neutralize it as completely as possible by a network simulating the earth in its electrical properties. The attempt is made to approach a "null" with this network, and the values necessary for this condition are recorded.

An improvement in technique which deserves mention, is the so called "continuous profiling" technique. In this, a truck or tractor with spiked metal wheels serves as a means of making contact with the ground. Measurements can thus be taken while the electrodes are in motion.

In magnetic equipment, we find improvements of more or less routine nature in the familiar field balance.

Work has progressed in the construction of the earth inductor apparatus, suitable for field measurements of magnetic intensity to better than one gamma.

Techniques have been developed for core orientation by magnetic methods. One system rotates the core sample inside a coil, thus enabling the operator to measure the direction of the magnetic axis in the piece, or if desired, its polarization.

Improvements in radioactive equipment include those made in the direction of improving the Geiger-Müller tube. The background count of the tube has been reduced, and the working voltage made lower. A suitable type of tube operates at approximately 500 volts, and has such a flat characteristic that this voltage may be varied plus or minus 50 volts with little change in the counting rate. A new type of portable Geiger-Müller apparatus has been developed, employing small batteries which make it independent of any other source of energy. A modification of this same type has been developed for laboratory use, and is designed to operate from the standard 60 cycle power supply.

The technique of what might be called "radioactive coring" by analogy with electrical coring has grown up, and has had some experimental use in this country and abroad. One type of apparatus makes use of a cartridge containing an ionization chamber and electroscope, the entire system being lowered to the desired depth in the bore hole, allowed to remain for a time, and then raised for observation. A more convenient type employs the Geiger-Müller tube and one amplifier tube in the cartridge, the remainder of the apparatus including the

mechanical counter remaining at the surface. This system promises to allow "coring" through the casing; an operation difficult, if not impossible by other methods.

Improvements in geothermal methods appear confined to those utilizing the resistance thermometer. The resistance elements have been improved, making for more rapid response, in turn allowing a higher speed of lowering during measurement. Cable has also been improved, as have the instruments for automatic recording of temperature against depth.

Considerable interest has been displayed in geochemical methods. As far as the author is aware, these have been restricted to the search for oil and gas deposits.

One class of investigators utilizes soil samples which are collected and sent to the laboratory in ordinary glass jars. Another class utilizes samples of gas; in one case allowed to collect in a pipe driven into the earth; in another pumped up from the pipe immediately after driving. In the case of the soil samples, the sampling equipment is somewhat primitive and need hardly be discussed.

While a variety of methods have been developed for analysing the gas or soil samples, all are rather complex, as is to be expected when one considers the small concentrations of the sought-for constituents. These concentrations will vary between one and 25 parts per billion by weight. When this is considered, together with the fact that materials having very similar properties must be separated and estimated independently, the complexity of the problem can well be realized. The usual procedure involves removing the water vapor from the sample, then following with the removal of ammonia, and carbon dioxide, since both of the latter will interfere with analysis. Analysis is then made for quantities of methane, ethane, propane, butane, and higher members of the paraffin series. Some investigators analyse for the altered products of the substances mentioned, others analyze for members of the paraffin series above and including hexane, still others analyze for other products believed to be related to the presence of underlying oil deposits.

In all cases, the apparatus is so complex and fragile, that it is operated only in the laboratory. This is in contradistinction to other types of geophysical equipment which are brought to the area under examination. Thus far, as far as the author is aware, this limitation has not been found troublesome, since it is believed that the samples

suffer no change between their removal and their arrival at the laboratory.

In bore hole instruments, there have been developments aside from those mentioned in connection with radioactive and geothermal equipment. Several new systems of electrical coring have been announced, these differing in employing single and double probes, in place of the usual number of three or four, and further in employing alternating current in place of the direct or commutated direct current utilized in the past. While results of work with these methods are not available, it is believed that they will give information in addition to that gained by direct current resistivity measurements. A system employing ultra high frequencies has also been announced, but the results of field tests are not yet available.

Well-surveying instruments, probably the oldest type of bore hole instruments, have also been improved during the past year. The increasing depth of wells has made it necessary to build apparatus to withstand the higher temperatures encountered. It is not at all unusual nowadays for the temperature at the bottom of the well to be in excess of 240°F. Both clockwork mechanisms and film have been improved to allow use at such temperatures.

Undeniably, improvement in geophysical equipment has been taking place at a rapid rate. Except for the fact that this improvement involves in some cases a fearful obsolescence cost, the record of the past year is a truly heartening one.

REPORT OF THE YEAR'S ACTIVITIES IN ELECTRICAL, GEOTHERMAL, RADIOACTIVE, AND SOIL ANALYSIS METHODS*

C. A. HEILAND†

At the outset I want to acknowledge the splendid cooperation which I have received in the preparation of this report by the members of my committee.[1] Their support has been most gratifying, and the information received from them on progress in our field in the last year is so complete that I doubt whether I can do justice to their contributions in the space allotted to the report.

The year's activities in electrical, geothermal, radioactive, and soil analysis methods will be covered in this report in the order given. Each of these will be subdivided into applications in mining, oil exploration, engineering geology, and activities along scientific or theoretical lines.

I. ACTIVITIES IN ELECTRICAL PROSPECTING

MINING

Considerable activity in the field of electrical prospecting in mining in the past year is being reported by Hans Lundberg. He has carried out geophysical surveys in New Brunswick, northern Quebec, northern Ontario, British Columbia, and in New Jersey, Pennsylvania, Virginia, Wyoming, Utah, and Colorado. The commercial objective of these surveys was the location of orebodies of nickel, copper, lead, zinc, and quartz veins; furthermore, the determination of structures associated with the occurrence of gold deposits. The total amount of work done amounted to 42 surveys in 1938, coverage of 25,000 acres, and a total of 3,000,000 feet of lines. Most of the work was done with alternating current potential methods but was supplemented in many cases by magnetometer work. The work extended not only to surface surveying but involved also underground work. By such surveys indications from ore, water courses, faults, and shear zones could be located. In his report, Lundberg stresses the fact that most work has been carried out in close coordination with geological

* Paper read at Geophysical Section, A.I.M.E., New York, Feb. 15, 1939.

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[1] Subcommittee for Electrical, Geothermal and Radioactive Methods, American Institute of Mining and Metallurgical Engineers.

surveys. Electrical instruments have been improved so that they are now adaptable not only to the higher audio frequencies but also the low frequency range.

Riddell has likewise been very active in electrical and magnetic surveys of Canadian mining districts. He has been particularly successful with these methods in the Sudbury region where he covered an area about six miles long and one mile wide. This was checked during the last year by drilling to the extent that in all cases the areas indicated by the magnetometer and resistivity methods were verified. Many of the ore lenses found were not of high enough grade; however, a 15-foot vein of massive sulphides consisting of pyrrhotite and chalcopyrite and averaging about $30 per ton more than made up for the lack of values in the other discoveries.

Malamphy has been very successful with self-potential measurements at the Haile mine near Kershaw in South Carolina. About 50 drill holes testing the anomalies found had been completed by September 1, last year. Most of them found pay ore, but a great many anomalies still remain to be tested. Most important of the discoveries was an extension of the orebody from which the mill had been operating and the discovery of an entire new orebody estimated to be larger than any ever before discovered on the property. A direct result of the geophysical operations has been the addition of a mill so that the total capacity is now more than twice of what it was before November, 1938. An article dealing with gold mining on this property was published in the *Mining Congress Journal* of October of last year, and Malamphy informs me that he will present a paper on the geophysical work at an early date.

The Areal Geological and Geophysical Survey of Australia has been carrying on a very ambitious program in northern and western Australia for the past three years. The reports covering the activities of the years 1935 and 1936 have just been received. The self-potential, resistivity, Racom, electromagnetic, and magnetic methods were used; most of the early work was done by the Electrical Prospecting Company of Sweden (Aktiebolaget Elektrisk Malmletning). The reports are accompanied by a set of large and instructive maps showing magnetic anomalies, magnetic profiles, potential gradient contours, self-potential anomalies, in-phase and quadrature components of electromagnetic fields and resistivity curves in several areas. The work done is so extensive that it would take the entire space allotted for this report to describe it fully and to do it justice.

The same company reports extensive work with the intensity and phase ratiometers (Turam method) which was described in a paper before this group two years ago; the work was done in Sweden, Finland and Norway. This company has also taken up gravity work in mining on a comparatively large scale which is reported in greater detail in Kelly's report in the Annual Review Issue of *Mining and Metallurgy*.

The Geophysical Department of the U. S. Geological Survey conducted stratigraphic investigations with resistivity methods in Michigan, worked on faults in the Kentucky fluorspar area, and applied the resistivity methods also to the location of underground water in the Hawaiian Islands.

Kelly has used his ground comparator, magnetic, resistivity, and spontaneous polarization methods in various areas in Canada on which he has given details in his annual report.

Several geophysical journals in Europe have recently carried a number of articles dealing with so-called wireless geology; however, the articles are of a rather general nature, and it remains to be seen what practical results can be accomplished. In this country, Fisher has reported on a new instrument for which a depth penetration of 450 feet is claimed at a frequency of 175 kilocycles. This is somewhat open to question; if the theory of electromagnetic radiation can give us a clue as to the practical possibilities of radio methods, the chances for getting much energy down to an orebody and back do not appear to be very great at these frequencies. A simple calculation shows that at a frequency of 10^5 cycles, a formation 125 feet thick absorbs 50% of the radiation if its resistivity is 10^5 ohm-cm.; however, if the resistivity is 10^4 ohm-cm., 90% of the radiation will be absorbed. Barret has also conducted extensive experiments with high frequency methods; however, his statements in regard to depth penetration are much more conservative. His Terrometer has been applied lately to both placer and vein deposits. He has also developed an instrument for the location of faults which has been applied chiefly in geophysical oil exploration. This leads us to the next section, a discussion of progress in the field of electrical oil exploration.

OIL EXPLORATION

Applications of electrical methods in oil exploration have been three-fold: measurements of electrical transients and related methods; resistivity methods; and electrical logging.

In connection with electrical transient and related methods, the

early observations made by Karcher and his associates in certain Kansas areas appear in an interesting light. Karcher's objective at that time was a determination of the self-inductance of the input circuits; he has been good enough to write me regarding it and stated that according to his experience the percentage change in self-inductance was invariably greater, and for certain electrode separations two to three times as great, as the changes in resistance due to the same subsurface electrical characteristics.

Rosaire, in his work with electrical transients and other low-frequency alternating current methods, evaluates his results in terms of a time constant related to the resistance and the capacitative reactance of the ground circuit. In his paper published in the March, 1938, issue of GEOPHYSICS, he comments on anomalies obtained on several deep Gulf Coast fields such as Satsuma, Fairbanks, Aldine, Van Vleck, South Elton, Sandy Point, and Segno, and finds a definite relationship between refraction anomalies, exaggerated reflection dips, shallow drilling rates and distribution of heavier hydrocarbons. This has led him to believe that deep oil fields may be reflected in shallow stratigraphic variations; going a step further, the conclusion is that oil accumulations due to stratigraphic traps which cannot be found by geophysical methods of structural exploration may be located if associated with resistance, reactance, hydrocarbon, and other variations in the overlying section. In his paper, Rosaire made the rather significant statement that the depth penetration for the electrical transients does not appear to be greater than for like electrical methods under similar conditions. In this connection, an article by B. P. Hawley in the July issue of GEOPHYSICS is of interest. In experimenting with electrical transients in the San Joaquin Valley, Hawley could not find the "kinks and nicks" postulated for the transient method in the current or potential records; he states that the steady-state values were reached too rapidly to permit of correlation with known subsurface conditions. In the October issue of the same journal, S. S. West reports on an improved method for the determination of transient characteristic of ground circuits. He balances the e.m.f.'s produced by passing a non-sinusoidal alternating current of 50 cycles frequency and square shape between current electrodes, against a reference impulse of the same phase and amplitude; a network is inserted between the two component parts and adjusted, presumably in reference to resistance and capacitance, until the observed and the reference impulses are as closely identical as possible.

In connection with electrical structural prospecting, Jakosky's

mobile electrode consisting of a spiked wheel on a tractor deserves mention. An illustration is given in the Annual Review number of *Mining & Metallurgy*.

The Schlumberger Well Surveying Corporation has further perfected the process of electrical logging. Owing to the fact that original differences in resistivities of formations may be obliterated by invasion from the drilling fluid, it has been found advisable to run a so-called "third curve" which is taken with a greater electrode separation to effect greater penetration. Supplementing earlier findings in Russian fields that apparent resistivities of oil formations may give a clue to the productivity of the formation, experimental and theoretical investigations have been made for the purpose of deriving the approximate amount of oil present in a formation. As discussed in the article by M. Martin and others in GEOPHYSICS, the resistivity of a mixture of salt water and oil increases first slowly and then more rapidly with the amount of oil present; hence, after the true resistivity has been determined from the apparent resistivity by allowing for the effect of the drilling fluid in the flooded zone, after the porosity has been determined from the self-potential run and the salinity of the formation water from a specimen, it becomes possible to calculate the percentage of oil present in the formation. To supplement information given by electrical logging, the Schlumberger Well Surveying Corporation has perfected a mechanical side wall sampler which is described in more detail in the September 26 issue of the *Oil Weekly* of last year.

ENGINEERING

A certain amount of electrical exploration has been done in the past year in connection with dam sites. The company with which I am affiliated conducted some electrical tests in connection with seismic refraction work on a number of projects for the U. S. Reclamation Service. Some of the work was done for the purpose of determining depth to bedrock in connection with the 13-mile Grand Lake-Big Thompson Canyon diversion tunnel through the Continental Divide. Reports of verification of the predictions by drilling have just been received. As reported by Goldsmith, resistivity methods have found applications in connection with corrosion problems. It was found that excessive corrosion occurred in soils having resistivity less than 2500 ohm-cm., in ground whose acidity amounted to more than 500 parts per million, and where the pipe crossed ponds or streams of excessive acidity.

THEORETICAL WORK

A number of papers published last year have dealt with the extension of the two-layer resistivity theory to three-layer problems. Following an article by W. W. Wetzel and others, the subject was discussed by R. J. Watson and J. F. Johnson in the January, 1938, issue of GEOPHYSICS. Of great interest in this connection is a publication by Evjen in the March issue of GEOPHYSICS, showing that the potential-drop-ratio method is superior in resolving power to the resistivity method.

On the borderline of electrical and seismic work, a recent article by Thyssen and others on the seismic electric effect is of interest. Following up early investigations on the same subject, the relation between the magnitude of the effect and the concentration of the electrolytic solution was investigated; the amplitude goes up rapidly with concentration, reaches a maximum and then drops with equal rapidity. The effect was likewise found to increase with the potential difference between the electrodes and the frequency of vibration. It was found that impulses can be recorded but that no true reproduction of the ground motion is possible; the seismic electric effect is closely related to the depolarization of the solution.

II. GEOTHERMAL INVESTIGATIONS

There appears to be no record of any geothermal investigations in connection with mining problems during the last year.

In connection with oil exploration, the activities of the Schlumberger Well Surveying Corporation should be noted. Systematic records of well temperatures taken together with resistivities of formations appear to have no less than five applications: (1) the location of high-pressure gas and oil sands; (2) correlation of formations between wells by their temperatures, regardless of whether the well is cased or not; (3) location of the flows of fluids into the well; (4) study of movements of fluids behind casing; and (5) location and study of cemented zones. The importance of taking temperature measurements in wells was also stressed in the last edition of Dorsey Hager's "Practical Oil Geology" published last year.

In the field of scientific studies of ground temperatures, L. B. Slichter pointed out that experiments on thermal conductivities at high pressures and temperatures are being made at Harvard.

C. E. Van Orstrand called my attention to a number of papers published on geothermal investigations during the last year. While

all of these cannot be reviewed here, two of them at least are of interest. One of them by E. C. Bullard deals with the effect of topography on the distribution of isothermal surfaces; the author comes to the conclusion that for moderate relief between wells the correction due to terrain is insignificant, while in mountainous areas it may attain considerable values.

Van Orstrand himself investigated ground temperatures of lava beds in Oregon, and found that in general the source of heat could be attributed to the lava beds themselves; in one area, extraordinarily high temperatures approaching the boiling point were due to an adjacent mountain mass or intrusion.

An investigation by Dahlblom on crustal temperatures is noteworthy in which temperatures of deep mines in the Witwatersrand area in South Africa were utilized. The author came to the conclusion that the decay of radioactive products contributes more to earth temperatures than is generally appreciated; therefore, the temperature gradient is less than should be expected if the earth's interior were the only source of heat; this in turn leads to the conclusion that temperatures near the Curie point may occur at greater depths than generally assumed.

III. RADIOACTIVITY

According to word received from Slichter, investigations at Massachusetts Institute of Technology on age determinations of rocks by radioactive methods are proving exceedingly interesting and are clearing up the possibilities and limitations of the helium method. According to Lane, the report of the committee on Measurement of Geologic Time of the National Research Council indicates that at last an agreement on determinations of radioactivity by the new Evans alpha-helium method and the older radon-thorium-helium method has been reached and that probably all previous work on radioactivity age determinations requires considerable revision. Lane also reports increasing interest in the determination of radioactivities of oil well samples.

IV. HYDROCARBON SOIL ANALYSIS

I have taken the liberty of including this increasingly important field of geophysical exploration in my report, because it appears to be more closely allied with radioactive measurements than with any other method. Rosaire reports that in addition to the work on the Gulf Coast previously mentioned, he has conducted surveys in the

Permian basin, the Illinois coal basin, south Arkansas, and the Mid-Continent, combining the soil analysis and Eltran method. It has been found that sediments overlying favorable and possibly productive structures are characterized not only by transient anomalies as previously reported, but also by "halo" patterns of the heavier hydrocarbons. Like the electrical indications, these hydrocarbon effects do not appear to be related to depth nor the relief of underlying structure. Such phenomena have been observed over typical stratigraphic traps as well as over structures of appreciable relief. In Rosaire's opinion, stratigraphic prospecting methods are, therefore, primarily adapted to reconnaissance, while the function of structural prospecting methods will remain the determination of depths and relief of structure. An article by Rosaire published in the December 22 issue of the *Oil and Gas Journal* of last year sets forth these conclusions in somewhat greater detail.

In conclusion I want to express my thanks to the members of this committee who have so generously contributed to the success of this report.

REPORT OF HOUSTON GEOLOGICAL STUDY GROUP IN INTERPRETATION OF GEOPHYSICS*

The Study Group in the Interpretation of Geophysics held seven meetings, some of which were attended by as many as twelve members. The leader, Mr. Paul Weaver, led the group with a series of fine lectures. The members of the group were at liberty to interrupt the lectures at any time to ask questions or offer discussion.

A. Two different types of geophysical pictures were discussed: type 1 in which the anomaly is so strong and is measured on such physical properties that both the kind of material causing the anomaly and the shape of the anomalous mass can be deduced; and type 2 in which the anomaly is small and caused by rocks whose physical properties differ but slightly from the surrounding rocks and therefore both the kind of material and the shape of the anomalous mass are difficult or impossible to deduce.

1. Three examples of the first type were discussed:

a. *Strong Magnetic Anomalies.*

There are only a few minerals which are para-magnetic; that is, show an effect in the earth's magnetic field, and of those only magnetite and ilmenite are found in any widespread quantity, with the exception of certain very rare localities where franklinite, pyrrhotite, or some of the others may occur in abundance. Therefore in practically every case a strong magnetic anomaly measures a large quantity of magnetite or ilmenite in some mass of rock. Magnetite and ilmenite are found in both basic and acidic igneous rocks and in sediments derived from them, but strong anomalies of great extent almost always show basic rocks, as both minerals strongly favor basic rocks. Strong anomalies of small areal extent may be concentrations of magnetite in granite wash or other sediments or may be due to magmatic concentrations in igneous rocks. As there are no minerals which show an appreciable negative magnetic effect, magnetic lows are merely returns to base level between magnetic highs. However, Heiland thinks that some negative anomalies are caused by overturning of magnetic rocks.

b. *Strong Gravity Anomalies.*

Salt is one of the most conspicuous of sedimentary rocks as to density. It has lower density than any other rock except very recent unconsolidated sediments and some of the diatomaceous shales. Therefore, good-sized minima can usually be attributed to salt and the shape of the mass can be rather readily determined within certain limits, unless two or more anomalies overlap. The basic igneous rocks are very conspicuous for their high density and most large maxima can be attributed to masses of basic igneous rock. More rarely granites or thick limestones in contact with young sediments may produce large maxima. Strong maxima of small areal extent may be lime or anhydrite caprock or the smaller-sized igneous intrusives.

c. *High Speed Refraction Seismic Anomalies.*

Salt, limestone, anhydrite, granite and basalt all have very high seismic velocities. When masses of any of these are in contact with other rocks, especially younger sediments, strong anomalies can be mapped by the refraction seismograph. The contrast between the velocity of the salt or other anomalous rock, and the velocity of the surrounding country rock, especially if the latter is unconsolidated, may be more than three to one. When the velocity of the anomalous mass is found to be about 14,000

* Paper read by A. B. Miller at a meeting of the Houston Geological Society. It is thought that this may be of some interest to our members.—Editor.

feet per second, the rock is either salt, limestone, anhydrite, granite or basalt. If the velocity is 16,000 feet per second or over, then the anomalous rock is either salt or granite. It may, however, be very old and very massive limestone or anhydrite, or it may be basalt, if the path is not close to the surface. The regional geology of the area will usually aid in the determination of the kind of rock which is causing the seismic anomaly; for example, in the Gulf Coast the mass would of course be a salt dome or its caprock and in West Texas it would probably be an igneous mass or massive limestone or anhydrite.

2. Three examples of the second type were discussed. In this type, the anomaly is small and caused by rocks whose properties differ but slightly from the surrounding rocks. These weak anomalies may be difficult to interpret because the effect of the anomalous mass is obscured by the effects of shallow formations which cannot be computed separately. Also, weak anomalies must be centered in an area of monotonous geophysical character in order to be interpreted, as it is very difficult or impossible to distinguish between two or more weak anomalies which are close together and to calculate anything definite about either one.

a. *Weak Magnetic Anomalies.*

Sedimentary beds containing magnetite or ilmenite may sometimes be mapped at the outcrop by the magnetometer. This is because the magnetic mineral, being heavy and less soluble, is left behind during weathering and solution. However, when the bed containing excess magnetite is at considerable depth, it is very doubtful if the structure of the bed can be mapped; because even in the most favorable case the contrast between the magnetite bearing sediments and the surrounding beds is only slight, and the magnetic effect of basaltic or granitic rocks in the basement may be much greater.

b. *Weak Gravity Anomalies.*

Weak gravity minima standing alone can be used provided there are no serious surface effects on the instrument, but it is difficult or impossible to distinguish between a salt plug at great depth and a syncline or graben. Also weak maxima or minima are easily obscured by a strong regional variation of gravity from the basement.

c. *Weak Reflection and Refraction Anomalies.*

Mapping of limestone, salt or anhydrite masses that are surrounded by Paleozoic rocks is difficult because the velocity contrast of a path through them and one through the normal section is slight.

The same is true for deep salt domes, even in areas of Tertiary sediments, because the path to reach a deep dome must pass through so many beds that the path through the salt is only a small part of the total path. Therefore variations in the sedimentation and consequently in the velocity of those beds surrounding the salt may give more variation in the observations than does the presence or absence of salt in a small portion of that path.

Similarly with reflection shooting, mapping of deep structures having small closures shallow structures with very low relief, convergence of beds, and other stratigraphic traps, is difficult, because the contribution to the travel time of the seismic wave by the overlying beds, especially the surface (low velocity) beds, may mask the difference in depth to the beds in question.

It is the purpose of some of the recent new geophysical methods to find these structures, which give weak anomalies by the older geophysical methods. It is, however, believed that more refined procedure by the old methods might have a chance to increase their success. For example, it was suggested that in reflection shooting, it

might be possible to find the existence of a structure by studying the number and apparent spacing of reflections at each location; such data might indicate local compaction, changes in sedimentation, or convergence of geologic section on structures, which dip computations on a phantom horizon did not show clearly.

B. *Geophysics of the Soils.*

Because of the importance of the properties of the shallow beds and the soil in affecting weak anomalies the concluding lecture was devoted to the physics of soils. It was mentioned that the physical characters of the soil depend mostly upon the climate, vegetation, and topography, rather than upon the parent material from which the soil was derived. This means that in rather rough country with differences in cultivation, there is marked variation in the physical properties of the soil.

C. Numerous references were given by Mr. Weaver during the lectures, some of which are listed:

1. Barton, Donald C., "The Seismic Method of Mapping Geologic Structure," A.I.M.E., 1928.
2. Hotchkiss, Rooney and Fisher, "Earth-Resistivity Measurements in the Lake Superior Copper Country," Tech. Paper 82, 1928.
3. Jakosky, J. J., "Geophysical Studies in Placers and Water-Supply Problems," Tech. Paper 515, 1933.
4. Jakosky, J. J., "Operating Principles of Inductive Geophysical Processes," Tech. Paper 134, 1928.
5. Keen, B. A., "The Physical Properties of the Soil," 1931.
6. Lundberg, Hans, "Practical Results Obtained from Geophysical Surveys," Tech. Paper 954, 1938.
7. Slichter, L. B., "Certain Aspects of Magnetic Surveying," Tech. Paper 120, 1928.
8. Stearn, Noel H., "The Dip Needle as a Geologic Instrument," Tech. Paper 151, 1928.
9. Sundberg, Karl, "Electrical Prospecting for Molybdenite at Questa, N. M.," Tech. Paper 122, 1928.
10. Tagg, G. F., "Interpretation of Resistivity Measurements," Tech. Paper 477, 1932.
11. Wolfganger, "Major Soil Divisions of the U. S.," 1930.

THE SOCIETY ROUND TABLE

ACKNOWLEDGMENT

With this issue, the editorship of GEOPHYSICS passes from my hands. It would have been impossible for me to have edited with some success these last nine issues of GEOPHYSICS without the splendid cooperation of all the authors, the many members of the Society who acted as referees, and our printers, the George Banta Publishing Company. To this large host of friends, I extend grateful thanks. In particular, to E. E. Rosaire for his work in undertaking the advertising business for us for more than a year, to our Secretary-Treasurer, H. B. Peacock, and his predecessor, Miss M. E. Stiles, to our Business Manager, J. F. Gallie, to the assistant editor, C. E. Houston, and to Miss Vara Doherty for their untiring assistance whenever needed, I feel eternally grateful.

M. M. SLOTNICK
Editor

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee have approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

John Lowell Bible
Joseph A. Sharpe, Raymond T. Cloud, Joseph D. Eisler

Henry William Busch
Wilton W. La Rue, Jack N. Nahas, Burton McCollum

David Raymond Dobyns
Henry C. Cortes, J. C. Pollard, J. P. Minton

Edward Staniford Foster, Jr.
Paul W. Klipsch, Leo Horvitz, E. E. Rosaire

Joseph Robert Gilliland
R. Clare Coffin, Joseph A. Sharpe, Joseph D. Eisler

Sigmund Immanuel Hammer
E. A. Eckhardt, L. L. Nettleton, George B. Lamb

Charles Coyle Lash
Chester J. Donnally, Dean Walling, Henry Salvatori

Joseph Le Conte
Chester J. Donnally, Henry Salvatori, Drexler Dana

John Augustus Lester
Henry C. Cortes, J. C. Pollard, J. P. Minton

John Patterson Lukens
Ewin D. Gaby, W. D. Neff, Frederick Romberg

John William Mathews
Chester J. Donnally, Drexler Dana, Henry Salvatori

Vincent Miller
William Henry Courtier, A. J. Hintze, R. L. Doan

Hiram Reginald Moorman
H. W. Merritt, H. G. Patrick, Glenn E. Bader

Wesley Hubert Seifert
J. P. Minton, J. C. Pollard, Henry C. Cortes

Kenneth Harold Waters
L. H. Wise, Edward L. De Loach, John A. Gillin

Paul Atwood Whitney
G. W. Carr, I. M. Griffin, Jr., A. D. Kerns

ASSOCIATE

Daniel Germer Egan
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Chester J. Donnally, Henry Salvatori, Drexler Dana

Richard Pierrie Johnson
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Henry Salvatori, Chester J. Donnally, Drexler Dana

George Henry Wessler, Jr.
W. M. Rust, Jr., Derry H. Gardner, C. C. Nash, Jr.

THE NINTH ANNUAL MEETING OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS

The ninth annual meeting of the Society of Exploration Geophysicists was held in Oklahoma City, Oklahoma, March 21–23, 1939. Although all who attended the sessions did not register, 196 members and 164 non-members registered, a total of 350. The registration and attendance were the greatest thus far enjoyed by the Society. Dr. F. M. Kannenstine arranged the excellent program of papers (reprinted below without deviations from the printed program having been noted), and each session was well-attended.

PROGRAM OF THE NINTH ANNUAL MEETING HUCKINS HOTEL, OKLAHOMA CITY, OKLAHOMA, MARCH 21–23, 1939

TUESDAY, MARCH 21

8:00 A.M. Meeting of Nominating and Executive Committees
9:00 A.M. Registration
10:00 A.M. Business and Technical Session, Huckins Hotel
12:15 P.M. Luncheon, Huckins Hotel
2:00 P.M. Technical Session, Huckins Hotel

WEDNESDAY, MARCH 22

9:30 A.M. Technical Session, Joint Meeting with American Association of Petroleum Geologists, Skirvin Tower Hotel
2:00 P.M. Technical Session, Huckins Hotel

THURSDAY, MARCH 23

9:00 A.M. Technical Session, Huckins Hotel
1:00 P.M. Technical Session, Huckins Hotel

PAPERS

Tuesday, 10 A.M.

Technical Session—F. M. Kannenstine, presiding—Huckins Hotel

1. An Areal Plan of Mapping Subsurface Structure by Refraction Shooting—L. W. Gardner
2. An Experimental Study of Changes in Reflection Character with Geophone Depth—H. M. Houghton
3. The Physical Significance of Correlation Coefficients—W. M. Rust, Jr.
4. Some Comparisons Between Straight and Curved Seismic Paths—M. Mott-Smith
5. Seismic Paths, Assuming a Parabolic Increase of Velocity with Depth—Charles E. Houston
6. Some Experiments on the Characteristics of High Frequency Waves in the Earth—L. G. Howell, C. H. Kean, R. R. Thompson

Tuesday, 2 P.M.

Technical Session—F. M. Kannenstine, presiding—Huckins Hotel

1. La Rosa Field, A Geophysical Discovery—Barney Fisher
2. Geophone Band Tests—R. S. Dahlberg, Jr.
3. Dip Reflections on Two Gulf Coast Faults—F. F. Campbell
4. Velocity Stratification as an Aid to Correlation—Roland F. Beers
5. A Proposed Method for Orienting Cores—V. V. Vacquier
6. A Note on a Device for Rapid Adjustment of Misclosures—M. M. Slotnick
7. Determination of Density for Reduction of Gravimeter Observations—L. L. Nettleton
8. Terrain Corrections for Gravimeter Stations—S. Hammer
9. Model, Mechanism and Field Tests of a New Type Gravity-Meter—Hart Brown

Wednesday, 9:30 A.M.

Technical Session, Joint Meeting with American Association of Petroleum Geologists—Donald C. Barton, R. W. Laughlin, presiding—Silver Glade Room, Skirvin Tower Hotel

1. Address of Welcome—Honorable Reford Bond
2. Correlation of Crude Oils with Special Reference to the Gulf Coast Crude Oils—Donald C. Barton, President, American Association of Petroleum Geologists.
3. Some Vertebrate Fossils of the Texas Gulf Coastal Plain—E. H. Sellards, President, Society of Economic Paleontologists and Mineralogists
4. The Relationship of Geophysics to Geology—F. M. Kannenstine, President, Society of Exploration Geophysicists
5. The Origin of Black Shales—W. H. Twenhofel
6. Summary of Rocky Mountain Geology—John G. Bartram
7. Tectonic Developments Off the California Coast—Francis P. Shepard

Wednesday, 2 P.M.

Technical Session—F. M. Kannenstine, presiding—Huckins Hotel

1. Transients in Electrical Prospecting—II—Paul F. Hawley
2. Recent Developments in Eltran Prospecting—P. W. Klipsch
3. An Eltran Survey of Yoakum County, Texas—J. L. Lake
4. Shallow Resistivity Survey at South Elton, Louisiana—E. E. Blondeau
5. A Note on the Seismic Electric Effect—R. R. Thompson
6. Gamma-Ray Well-Logging—L. G. Howell and Alex Frosch
7. The Electrical Model Method for Structural Investigations—I. E. Rosenzweig

Thursday, 9 A.M.

Technical Session—F. M. Kannenstine, presiding—Huckins Hotel

1. The Divining Rod—Herbert Hoover, Jr.
2. The Determination of Water Sources in Oil Wells—Clarence R. Dale and Burton L. Delleney
3. Concentrations of Hydrocarbons in the Earth—Eugene McDermott
4. On Geo-Chemical Prospecting—I—L. Horvitz

Thursday, 1 P.M.

Technical Session—F. M. Kannenstine, presiding—Huckins Hotel

1. On the Strategy and Tactics of Exploration for Petroleum—III—E. E. Rosaire
2. Geophysical Education in a Department of Geophysics—James B. Macelwane, S. J.
3. Geophysical Education at an Engineering Institution—Dart Wantland
4. Core Samples From the Ocean Deeps—C. S. Piggott
5. Exploring Drill Holes by Sample Taking Bullets to Supplement Electrical Logging—Eugene G. Leonardon and D. C. McCann
6. The Role of Isostasy in Mountain Building—Malvin G. Hoffman

MINUTES OF THE ANNUAL BUSINESS MEETING HELD MARCH 21, 1939, AT THE HUCKINS HOTEL, OKLAHOMA CITY, OKLAHOMA

The meeting was called to order at 10:00 A.M. by the President, F. M. Kannenstine, Minutes of three meetings of the Executive Committee held during the year were read and approved.

A brief financial report was made by the Secretary-Treasurer. President Kannenstine then announced the results of the ballot for officers of the Society for the year 1939–40 as follows:

President, E. A. Eckhardt
Vice-President, W. T. Born
Secretary-Treasurer, J. H. Crowell
Editor, R. D. Wyckoff

No further business was brought before the Society and the meeting proceeded with the technical program.

Respectfully submitted,

H. B. PEACOCK
Secretary-Treasurer

REPORT OF THE SECRETARY-TREASURER OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS AT THE NINTH ANNUAL MEETING IN OKLAHOMA CITY, OKLAHOMA, MARCH 15, 1939

The financial condition of the Society of Exploration Geophysicists as of March 15, 1939, is shown by the following balance sheet:

ASSETS

Cash in Banks		
Austin National Bank (checking account)	$1,897.17	
Guardian Trust Company (checking account)	2,170.72	
Guardian Trust Company (savings account)	2,012.50	
National Bank of Tulsa (savings account)	1,511.93	$ 7,592.32

Accounts Receivable			
Advertising		367.50	
Subscriptions		16.60	
Reprints		95.53	
Back Numbers		132.64	
1938 Dues		181.50	
1939 Dues		2,029.50	2,823.27
Office Equipment			
Bookcase	$12.00		
File Cabinet	19.50	31.50	
Less: Reserve for Depreciation		1.50	30.00
			$10,445.59

LIABILITIES

Accounts Payable			
General			139.50
Surplus			
Excess of Income over Expense December 31, 1938		$5,597.66	
Excess of Income over Expense to March 15, 1939		4,708.43	10,306.09
			$10,445.59

The Operating gain of $4,708.43 for 1939, to date, is detailed as follows:

INCOME AND EXPENSE
MARCH 15, 1939

Income			
Advertising		$ 559.45	
Back Numbers		225.21	
Dues		3,817.00	
Reinstatements		10.00	
Reprints		41.67	
Subscriptions		583.25	$ 5,236.58
Expense			
Auditing		100.00	
Bond Premium		10.00	
Express and Freight		8.44	
Miscellaneous		20.03	
Postage		56.00	
Reprints		35.93	
Stationery and Office Supplies		70.15	
Stenographic and Clerical		200.00	
Telephone and Telegraph		2.10	
Traveling		25.50	528.15
Excess of Income over Expense 1939 to Date			$ 4,708.43

As of March 15, 1939, the Society had a surplus of $10,306.09. This surplus does not include approximately 3,700 copies of GEOPHYSICS stored with the Banta Publishing Company, publishers of the GEOPHYSICS, at Menasha, Wisconsin, with a minimum value of $2.00 each, or $7,400.00. The publications expense of $3,848.69, as shown by the 1938 audit, was more than equalled by the publications income of $3,969.62, for the first time in Society history.

The increase in membership is shown in the following figures:

Date	*Honorary*	*Active*	*Associate*	*Total*	*Increase*
1930	0	34	5	39	
1931	2	68	11	81	42
1932	2	83	11	96	15
1933	2	91	10	103	7
1934	2	141	23	166	63
1935	2	156	31	189	23
1936	2	195	34	231	42
1937	2	367	112	481	250
1938	4	510	158	672	192
1939	4	610	183	797	125

Respectfully submitted,

H. B. PEACOCK

Secretary-Treasurer

NOTICE OF ADDRESS OF BUSINESS MANAGER

Society Headquarters have been established in Austin, Texas, with the postal address:

J. F. Gallie, Business Manager,
Society of Exploration Geophysicists,
P. O. Box 777,
Austin, Texas

All letters pertinent to Society business, other than purely editorial matters, should be mailed to the above address. As heretofore, editorial matters should be addressed to the Editor.